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A Progress Report

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The Virtual Shipyard: A Simulation Model Of The Shipbuilding Process

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ABSTRACT

This paper describes a unique software program that simulates the dynamic complexities of the ship construction process. The program, called ShipBuild , was developed by Decision Dynamics, Inc. (DDI) under a Small Business Innovation Research (SBIR) contract sponsored by NAVSEA. The program greatly simplifies the planning and replanning process, making it easy to create a good production plan and keep it current. This simulation model of the shipyard production process captures both the essential physical shipbuilding activities and the essential management decision-making activities that support the physical production processes. The application consists of two independent submodels, a simulation capability and a results viewer component. The first submodel identifies the overall shipyard facility and manpower resources and the second identifies the construction tasks required to build a ship. The submodels interact to calculate the specific allocation of resources over time necessary to produce the ship.

The output generated from the program provides the durations and manhour loadings of elements of the ship construction process based upon dynamic resource availability. The output (unlike other scheduling programs for which durations are typically input and resource allocations an output) provides both schedule and resource use. Task durations are calculated based upon the manhour requirements, the number of people assigned and their productivity. Output generated by the application can assist Program Managers and Design Engineers in analyzing the manhour cost and schedule impacts of alternative designs and construction sequences. The program can also help to quantify the cost and schedule impact of delay and disruption as well as assist in identifying the most effective management actions to overcome such problems.

INTRODUCTION

Problem

Planning is the most critical and vexing problem in the shipbuilding process. To be successful, a strategic plan must integrate and manage the multitude of functions that are key to the construction process. Planners must learn how to minimize the impact that changes and delays have on plans and quantify their contribution to the total cost of a ship. What, for example, is the best construction sequence for a ship? How can engineers design a ship for the most affordable construction? How can a shipyard best utilize its resources during the construction process? How can the negative impacts of design changes and delays be minimized?

Designers and builders are continually challenged to find solutions to these complex questions. Yet answers to even the most difficult problems are eventually identified, plans are produced and the ship production process is begun. Unfortunately, the plans formulated to direct the project at the start are frequently upset by unexpected delays, unanticipated changes and unforeseen difficulties. Managers must decide how to reallocate resources to resolve each problem as it emerges. Revised plans are then needed to accommodate the myriad deviations from the original strategy. In severe cases of delay and disruption, managers must create new plans to replace versions no longer effective. However, creating and changing plans requires a tremendous amount of time and resources. Therefore, managers are often very reluctant to redo their plans unless things go terribly awry.

Solution

New management tools are being developed to help unravel complicated relationships and bring new understanding to the control of complex dynamic processes such as shipbuilding. This paper describes a unique, new software program that was developed to simplify the planning and replanning process. This application assists managers in creating a good plan and, more importantly, makes it easy for them to replan and to evaluate the effect of the revised plan.

This dynamic simulation of the ship construction process, captures the essential physical shipbuilding and management decision-making activities that support the production process. This is the first application of shipbuilding management theory embodied in a dynamic interactive simulation model. By capturing the complex set of feedback interrelationships that drive

dynamic behavior, the program is capable of quantifying manhour cost and schedule tradeoffs, tracking changes in productivity due to internal and external conditions, and replicating the disruption caused by delays and changes. The software consists of two independent submodels. The first identifies the overall shipyard facility and manpower resources and the second identifies the construction tasks required to build a ship. The submodels interact to calculate the specific allocation of resources over time necessary to produce the ship (Figure 1).

Key Features

Shipyard planners and managers can use the application to assist in analyzing the dynamic behavior of a sequence of related shipbuilding activities. The fabrication of components and the building, joining and outfitting of subassemblies, assemblies, blocks and zones are all types of activities that can be modeled in the program. Shipyard managers can simulate shipyard schedule changes and labor transfers in response to construction delays. These functions allow managers to accurately and quickly quantify the impact of

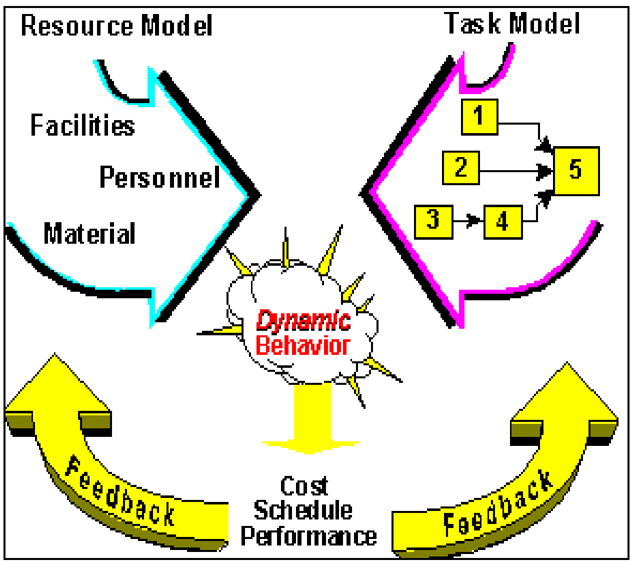

Figure 1. Model Operation

construction delays on manhour cost and schedule. The program tracks how the delays may trigger shifts in construction activity sequences, changes in schedule, and reassignment of the workforce among different tasks.

Feedback Structures

The simulation model offers three special advantages over conventional planning tools and traditional estimating models derived from statistical analysis of historical cost data. The first advantage is that real-world causal linkages between system elements are explicitly recognized and those links within the feedback structures that control system behavior are captured. Anyone examining the model can immediately understand both the logic of its organization and the meaning of its parameters. This transparency is essential to model validation. The more intelligible the model, the easier it is for the user to verify its logic and to rely on it for decision support analysis.

Second, because the application replicates system interactions, it provides far deeper insights into dynamic behavior than those derived from traditional static or econometric models. This insight gives shipyard planners and managers an intuitive feel for why tradeoffs arise over time, when they threaten substantial risks, and how they can best be resolved. A better understanding of the dynamic behavior of the ship construction process leads to improved performance and reduced costs.

Third, planners and managers are able to develop sophisticated "what-if?" scenarios for testing and analysis. Alternative schedules, design changes, or assembly sequences can all be easily defined and tested. Such "what-if?" testing provides a much broader analysis of construction delays and manhour cost and schedule impacts than can ever be obtained from simple manipulation of databases. The program provides a quantifiable basis for measuring the outcome of alternative management actions and creates a framework for controlled experimentation. Simulation lays a scientific foundation for accelerated advances in shipbuilding management.

Ship Hierarchy

The task submodel functions are organized into four activity types: ship, block, work package, and task. The activities are structured in a hierarchy sequence from ship down to task; the ship being the highest level in the hierarchy. To define the ship construction, the user must layout the activities required to build the ship and select various elements associated with the activities.

The ship layout is composed of individual tasks that come together to create interim products, called work packages. Work packages, in turn, are assembled into blocks and blocks are erected to produce the ship (Figure 2). Work packages may also be identified by unit and/or zone. The elements in this hierarchy are further defined by sequence dependencies in which the fabrication or assembly of any element may depend upon the prior completion of one or more other elements. In practice, the ship task sequence follows normal PERT (Program Evaluation and Review Technique) diagramming conventions.

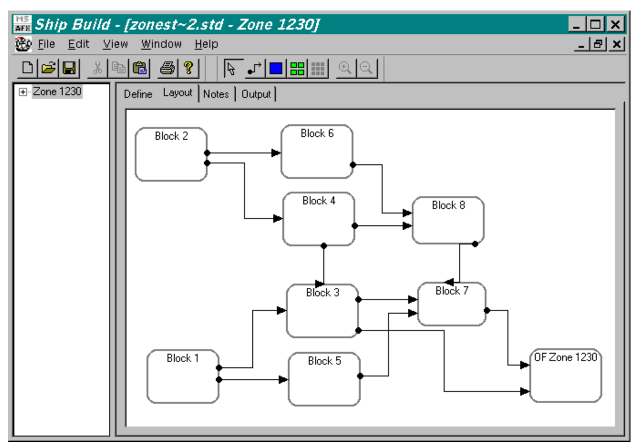

Figure 2. Ship Blocks Layout

Work Packages

Each work package is composed of one or more tasks which identify the work needed to create an interim product or to complete work at one construction site or stage. Interim products are defined not only by the tasks necessary to create them , but also by the following three additional variables:

- location (where the work is to be done),
- space (footprint size), and
- weight.

All three variables can be separately identified in the program.

Tasks

Each work package may include as many individual tasks (usually trade-related) as required to create the interim product. ShipBuild ™ is capable of simulating the effect of all of the many thousands of individual tasks that are involved in building a ship. These tasks describe the efforts necessary to create the many interim products which are developed during different stages of construction. Subassemblies (tasks) are joined to create assemblies (work packages), which are developed into blocks. Blocks are then erected and outfitted to produce the ship. These activities may be further defined by identifying sequence dependencies between one or more other elements in the hierarchy.

At the lowest level, only four variables define each task:

- work backlog (scheduled manhours to complete),
- labor resources (trade skills) needed to accomplish the work,
- equipment needed to accomplish the work, and
- dependencies (relationships to other tasks).

Shipyard Resources

The data from the shipyard submodel is used during simulation to dynamically assign resources to the work tasks to complete ship construction. The yard contains a labor force (identified by skill and trade) plus any number of work stations (identified by work type).

To define the shipyard layout, the user must identify the work stations in the yard by work type and the labor force by skill and trade. The shipyard submodel contains a facilities area where the main yard work stations and associated data are located (Figure 3). After defining the work stations in the shipyard, the user can specify elements associated with the work stations including:

- work type;
- equipment requirements and baseline productivity;
- days work stations are scheduled for activity; and
- lift, space and productivity associated with work stations.

At the yard level the user can also select policies that determine management responses to schedule pressure. The user may also define productivity losses due to such conditions as overmanning, overtime or lack of skills.

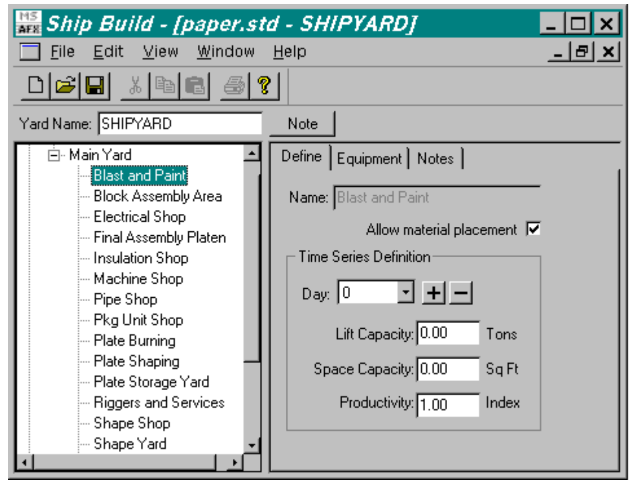

Figure 3. Shipyard Work Stations

The shipyard submodel also defines the labor resources of the yard (Figure 4), including:

- number of personnel (by trade and skill),
- number of shifts,
- baseline productivity of various shifts,
- time to hire, and
- baseline productivity of various trades.

The user can also define the labor items for each trade, and the separate skill levels for any trade.

Once defined, the shipyard facility and manpower resources can be altered to create new simulation results. Shipyard resources do not need to remain constant. Different yard configurations and facilities can be set up to test how changes during work will affect schedule and manning. For example, aged equipment or facilities may be phased out and replaced by modern, more efficient equipment or facilities during a simulation in order to assess how disruptions in process may affect production.

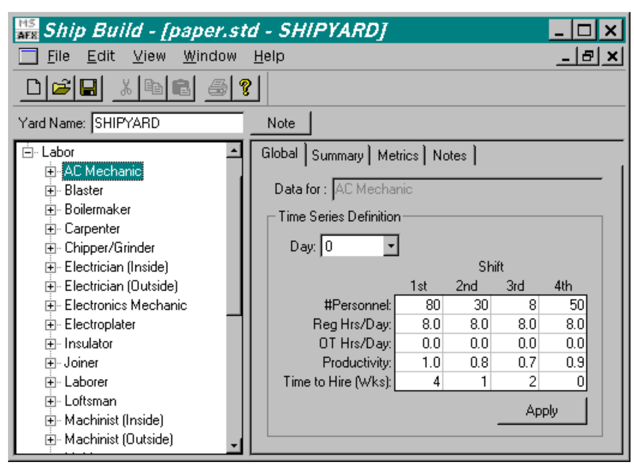

Figure 4. Shipyard Labor Resources

Default Data

The program supplies a default list of labor trades and work stations. The user can enter the total number of individuals assigned to each trade and each skill level within a trade at any time during the shipbuilding process. These numbers are applied to various tasks as appropriate during simulation runs. Unless the user has entered new data, the model is always ready to run using the default data. Default data values aid model development because the user can always check the impact of any data entries during model development.

Productivity

Unlike many other planning tools, the program incorporates a variable productivity function. Productivity is a function of an expected baseline productivity that is modified by such factors as learning, overmanning, skill mix, overtime and work sequence. The application generates these factors internally during simulation in response to changing shipyard conditions. For example, if a delay results in a period of overtime work, productivity for the overtime hours may be less than productivity depicted in the normal baseline.

Alternatively, if a task is late, overmanning may be necessary in order to regain schedule. The result of manning a task beyond the most efficient level is a reduction of productivity. It will take more actual manhours than planned to accomplish the work.

The software, uniquely, provides managers with the ability to assign the actual number of people to a job in order to accomplish it within the scheduled period of time as productivity per person decreases. Lower productivity values can also be assigned to work accomplished on second and third shifts, weekends or overtime.

Schedule Pressure

Another unique feature of this application is the ability to automatically calculate the need to assign more than the desired number of people to a task if, during a “what-if?” simulation, a task falls behind the baseline schedule date for that task. “Schedule pressure” is a non-dimensional multiplier applied to the desired number of people for a task (as established for the task in the ship construction submodel) to increase the number of people, or the amount of overtime needed to accomplish the task on schedule. If the number of people assigned exceeds the maximum number of people that can be efficiently applied to a task, then the productivity loss function will come into play. The program will then calculate how many budgeted manhours of work will be accomplished each day for the actual manhours expended.

Task Matching

During simulation, the computer regularly recalculates task needs and priorities. Task needs and resource availability are updated for every hour of every day until the construction process is completed. Task priority, a function of sequence, critical path and schedule pressure, determines access to resources. Tasks may only be accomplished at open work stations that specialize in the type of work requested. A blasting and painting task, for example, could only be accomplished at a blast and paint station. Some welding, assembly and equipment installation tasks, however, may be accomplished at a number of different work stations.

When a resource match is made, the task begins. While the task work is being performed, the resources utilized by the task are not available to any other task. In some cases, however, tasks with very high priorities may interrupt work in progress on non-critical tasks to gain quicker access to resources.

The multiple calculations for task matching and work accomplishment happen very quickly. In a matter of minutes, all of the thousands of tasks required to build a ship can be simulated.

Operation

During simulation, the model continually updates its internal schedules, computing new critical paths and tracking progress on all tasks and work packages. Output views of both Gantt charts and manning curves, are always available to the user.

Once a preferred baseline plan has been determined, the model may then be used to quantify the impact of design changes and delays on schedule and manning. By altering task definitions and work package sequences, changes can be simulated and compared to the baseline plan. Similarly, introducing delays by holding up various tasks will cause the model to seek "work around" solutions, causing out-of-sequence activities and even creating future rework requirements. Comparison of results to a baseline will show the difference in time and labor between two alternative scenarios.

When unexpected changes do occur during ship construction, planners often find it difficult to quickly replan activities and alter work sequences. The program offers a rapid method for replanning the entire production process or only a selected portion of the process. Replanning can be performed as often as desired and only requires that the change be identified in the model by appropriate changes to tasks and work packages.

Whenever a change or a delay causes the simulation to deviate from the planned baseline, tasks that are delayed begin to generate schedule pressure. As schedule pressure rises, it can trigger a variety of management actions. (These actions are dependent upon user-controlled settings.) For example, schedule pressure may translate into overmanning due to shifting labor among work stations. Alternatively, schedule pressure can be ignored in order to forecast what would happen without management intervention.

Output

The software provides program managers with the ability to successfully develop a strategic plan by integrating and managing the multitude of functions that are key to the construction process. The results achieved and the output available from simulation runs include:

- schedules for all tasks and for all interim products;
- overall ship schedule;
- labor manning (by shift and by trade);
- labor hours for all tasks, work packages, blocks; and
- total labor hours for the ship.

Thus the program will automatically transform a list of task manhour budgets and a list of yard resources into a schedule and manning forecast. Furthermore, the program will do it over and over again, in just minutes, helping planners discover the optimal task layout and the most efficient allocation of shipyard resources.

APPLICATIONS

To demonstrate the application of ShipBuild™ to a realistic shipbuilding situation, the construction of eight blocks in one zone of a ship was modeled. All stages of construction and manning estimates for each of the eight blocks were developed from historical data. Several different scenarios of the construction process were then evaluated, to demonstrate how the type of information generated by the program can assist design engineers and managers in the shipyard.

The eight blocks and their dependencies make up the center hull section of a cargo vessel. Blocks 1 and 5 are adjoining Starboard Side Blocks; 2 and 6 are Port Side Blocks. Blocks 3 and 4 are starboard and port deck blocks, respectively, inboard of 1 and 2, and 7 and 8 are inboard of 5 and 6.

Using the capabilities within the program, the blocks and the connecting arrows depicting sequence dependencies, were quickly developed (Figure 2). Similarly, the dependencies of the various work packages that create each interim product were identified and drawn (Figure 5) as were the tasks within each work package. After creating the logic diagrams, the details of each task were added, including total manhours budgeted for the task as well as labor resource requirements.

Next, the dependencies among tasks were defined (Figure 6). The prior tasks can be those within the same work package or any task in another prior work package. This is another important area in which this software differs from most conventional scheduling programs. Instead of using lag as a specific duration in days or weeks, lag is entered as a percentage of the preceding task's duration (since the preceding task duration is yet to be determined by the simulation run). The default relationship is "finish to start" with no predefined lag.

Two model applications are presented: one with manpower constraints and one with an alternative

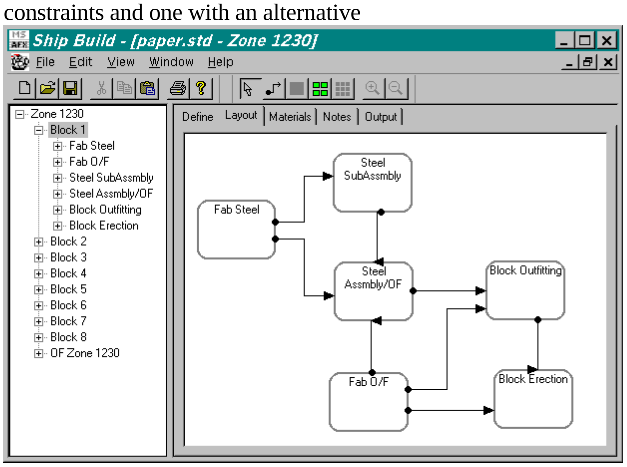

Figure 5. Work Package Layout

construction sequence.

Scenario One - Manning Constraints

In the first scenario, several different manning constraint policies were simulated to define the impact that the constraints would have upon the overall time and manhour expenditures for completing the work.

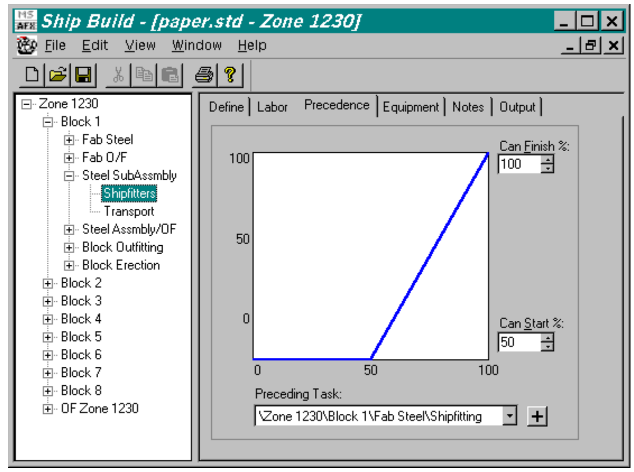

Figure 6. Defining Task Precedence

Figure 7 is a graphical display of three alternative situations. The baseline plot shows the planned cumulative manning curve for the project. The second curve shows the effect of a lack of personnel available at the start of the program. The total manhours remain the same, but the schedule is delayed. The third curve shows the effect of applying additional manhours, but at a lower productivity (due to overmanning) to complete the job on time.

The baseline plot (depicted by the blue line) displays the total number of planned manhours over the length of the project; approximately 340 days. The green line displays an increase in the number of planned project days resulting from a decrease in available labor. The red line curve describes an even greater increase in planned project days caused by overmanning with an associated lower productivity level.

The scenario in Figure 7, demonstrates the schedule and manning impacts of delay and disruption resulting from any interruption of the work process.

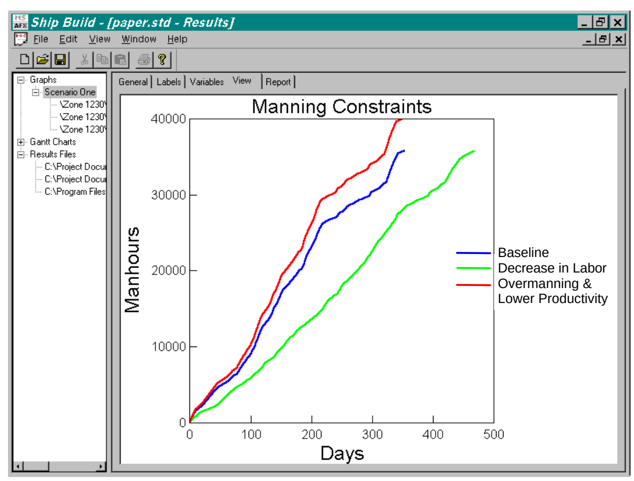

Figure 7. Manning Constraints

The unique capability of the program is best demonstrated by this type of scenario because the loss of productivity due to overmanning work packages or work tasks is taken into account in the simulation. The resultant additional cost in total manhours and/or the resultant additional time delay due to manpower

limitations can be described in tabular format, graphical format and Gantt charts.

Scenario Two - Construction Sequence Alterations

In the second scenario, a different block erection sequence simulation was compared to the baseline block erection sequence. The two simulations were compared to determine whether there were advantages from a manning or schedule duration standpoint for different construction approaches.

In Figure 8 the blue line again displays the baseline plot simulated in the first scenario. The curve depicted

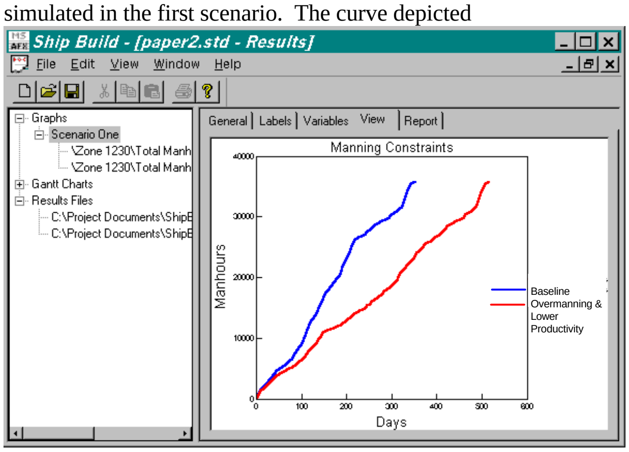

Figure 8. Comparison of Construction Sequences

by the red line in this scenario, describes a change in the block construction sequence. In the baseline simulation the blocks were constructed simultaneously. For example, blocks one, three, five and seven were simulated as one construction process and blocks two, four, six and eight as one process (Figure 2). In the second simulation, the blocks were developed sequentially with one followed by two, two by three, until all eight blocks were constructed. The red line curve indicates an increase in the number of project days required to complete the alternative construction erection sequence.

Results

The result of applying the simulation model to quantify real and potential delays and to identify alternative management actions to ameliorate those delays has the potential to save shipbuilders millions of dollars. Use of the software can produce a measurable reduction in both schedule and design change costs.

It should be clear from the model description, that this application can be used to explore not only real changes and events but also "what-if?" assumptions. By defining a series of "what-if?" scenarios, a model user can compare the relative impact of many different variables on system behavior. For example, alternative ship designs, task sequences, shipyard resources, problem areas and management responses can all be tested in a search for the best solution. Quantifying alternative "what-if?" scenarios also provides a very effective risk analysis tool. The model structure captures the complex set of feedback interrelationships that drive dynamic behavior. Thus the model can quantify manhour cost and schedule tradeoffs, track changes in productivity due to internal and external conditions, and replicate the disruption caused by delays and changes to the work.

Benefits

The ShipBuild™ model introduces a new generation of management and planning tools that can be used to complement or supplant current CPM (Critical Path Method) and PERT methods. The model runs on a PC (Personal computer) and has the power to track an extensive number of variables. This power translates directly into a more realistic representation of the shipbuilding process and therefore a more useful management tool. The software offers shipyards throughout the country the potential to gain a competitive edge in managing complex projects.

Use of the program will assist design engineers and shipyard planners in three important ways by increasing planning flexibility, control over work sequence, and confidence in the plan.

- Greater flexibility allows planners and managers to plan early, often and more effectively. Users can evolve plans that best address anticipated ship and yard conditions and quickly and efficiently replan whenever necessary.

- Providing planners with greater control over work sequence, task activities and resource allocation, ensures that the most important work gets done first and that manhour cost and schedule tradeoffs are clearly assessed.

- Use of the software provides planners with greater assurance that the plans are correct, that manhour cost and schedule can be safely predicted and that risks are reduced to a minimum.

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Shipyard Operational Improvement Through Process Management

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ABSTRACT

Under the Defense Advanced Research Projects Agency (DARPA) Maritech Program, the project, titled "Process Improvement Testbed for Shipyard Construction, Conversion and Repair," is applying state-of-the-art agile manufacturing and process improvement technology to ship construction, repair, and maintenance. DARPA's Agile Manufacturing Program has sponsored the development of a prototype suite of software tools, called ProcessTOOLS, for use in modeling and managing enterprises. Other research and commercial tools exist that can perform one or more of the modeling, scheduling, enactment, and simulation functions necessary for enterprise management. ProcessTOOLS is unique, however, in that all the functions are integrated into a single package and utilize a common representation. Using ProcessTOOLS, a shipyard maintains an accurate model of its operations, utilizes advanced scheduling techniques to assign process steps to shipyard resources, manages the execution of processes according to schedule, accurately monitors the status of processes in real-time, and simulates the shipyard forward in time from its current state to assess the impacts of a contract award, to forecast the effects of changes in internal processes, and to evaluate the probable delivery date of an order. By modeling a repair or construction job prior to bidding, ProcessTOOLS facilitates more detailed planning during estimation, which results in a more realistic bid. By providing continually updated status during production, ProcessTOOLS expedites just-in-time delivery of labor, material, and equipment to the job. Event information is archived as it happens during production to form a rich source for accurately measuring performance and realistically supporting future estimates.

INTRODUCTION

After decades of depending almost entirely on Navy ship construction and ignoring many commercial ship construction opportunities, the U.S. shipbuilding industry has been in economic doldrums. The Navy's orders for new ships have declined as a result of reductions in defense spending, and construction of large commercial vessels is handled mostly by highly-competitive foreign shipyards. Only 11.5 % of the $ 18.7 billion major U.S. shipbuilding dollars are for commercial contracts, and of that, only a fraction is for off-shore orders[1]. Past experience in other industries, such as the semiconductor and automobile industries[2], has shown that sustaining a market presence requires U.S. businesses to become commercially competitive in the global marketplace. U.S. shipyards need to increase commercial business to offset the reduction in Navy business, though international shipyards provide strong price competition, especially shipyards in the Far East and Eastern Europe. The international shipbuilding market is projected to pick up as oil tankers built in the 1970's come due to be replaced or refurbished, but U.S. shipbuilders are unaccustomed to competing in that market. The cruise shipbuilding market is also increasing, though European shipyards (Italians, Germans, Finns) have much of that business.

U.S. ship builders are being helped to attract a greater percentage of the world market. The Defense Advanced Research Projects Agency (DARPA) Maritech Program supports advanced technology development projects that will demonstrate improved practices and processes used for the design and construction of ships in the United States, surpass international competition, and yield significantly more affordable Navy ships. The Maritech Program is sponsoring a project, titled "Process Improvement Testbed for Shipyard Construction, Conversion and Repair." The principal goal of this project is to demonstrate a prototype suite of advanced computer-aided, enterprise management technologies called ProcessTOOLS, which were developed under DARPA's Agile Manufacturing Program as an enabling technology development and demonstration project. ProcessTOOLS is deployed at a small U.S. shipyard, and it will be used to support actual ship construction and ship repair projects. Improvements in shipyard operations realized by applying the advanced technology will be measured and reported.

The names, ProcessTOOLS and ProcessBASE, are herein associated with a research prototype and one of its components, respectively, and are not to be construed as belonging to any commercially available product.

The remainder of this paper begins with the project background information, which includes the process maturity model and agile manufacturing. Then ProcessTOOLS is summarized from two viewpoints: its functional capabilities and its architecture. Finally ProcessTOOLS use by individuals at several

organizational levels in shipyard is described.

BACKGROUND

The goal of this Maritech project is to improve construction, conversion, and repair operations in a real shipyard by applying state-of-the-art process technology using ProcessTOOLS. The approach is to develop a process improvement testbed at a small shipyard in which to apply the technology. In the process improvement testbed, the plan is to model the shipyard enterprise, manage shipyard functions using the models, and then measure quantitative process improvement based on a set of developed metrics. The early focus in modeling has been on Navy ship repair, maintenance, and shipyard administrative support. By the end of the project, modeling will be extended to cover ship construction and conversion, and commercial as well as Government contracts.

Through the performance of this contract, shipyards will gain a set of re-usable resource and process models, experience in applying ProcessTOOLS to actual shipyard operations, and useful metrics for measuring performance improvement. After a brief introduction to enterprise modeling, a model for ranking process maturity is presented. Agility, as it applies to the shipyard context, and the advantages of locating the testbed at a small shipyard are presented.

ProcessTOOLS and Enterprise Modeling

ProcessTOOLS is a suite of software tools for use in modeling and managing virtual enterprises. A virtual enterprise is a dynamic alliance of cooperating organizations where the resources of each are integrated to support a particular product effort for as long as it is economically justifiable[3]. Using ProcessTOOLS, an organization can begin to manage the impact of change to its business processes by planning and simulating potential alternatives. Process changes can be tested using the ProcessTOOLS software before any changes are implemented in the organization. ProcessTOOLS also supports real-time monitoring and control across geographically distributed units.

The key to managing change in an enterprise is understanding the enterprise itself. ProcessTOOLS facilitates this understanding by providing the capability to construct enterprise models. These models consist of:

- Products or services provided within or by the enterprise;
- Processes that are executed to manufacture products or provide services;
- Resources and capabilities needed to perform process steps;
- Flows that transport objects between process steps; and
- Material inventories, tool cribs, and information repositories that are involved in the process.

ProcessTOOLS provides a suite of special purpose editors that are designed to support the construction of high-fidelity enterprise models. These models can be executed to either manage the actual operations of an enterprise, or to simulate the operations.

Process Maturity Model

In describing how to re engineer business processes, Hansen[4] draws a sharp distinction between the traditional continuous improvement (CI) and total quality management (TQM) philosophies, and a more pragmatic approach that implements these philosophies by utilizing computer-aided analysis to manage and improve process performance. The model used to characterize the maturity of processes was originally created for software development by the Software Engineering Institute and generalized by Hansen[4] into the Process Maturity Model shown in Table I. At the higher levels of process maturity, improved productivity and quality are realized.

In shipyard operations, process maturity varies between Level 1 and Level 2. The Government requires documented Test and Inspection Plans, which enforce mandatory procedures for Quality Assurance (Level 2). Although the quality inspection procedures are rigorously defined, some production processes, such as painting, which depends on the weather, are less stringent and rely on quality inspection to catch errors.

Level	**Characteristics**	**Supported by**
Level 5 **Optimizing**	Improvements Fed Back into the Process	Modeling and Simulation
Level 4 **Managed**	Process Defined and Measured	Statistical Process Control Data Collection
Level 3 **Defined**	Process Defined with Standardized Results	Flow Charts and Process Maps
Level 2 **Repeatable**	Process Informally Defined with Predictable Results	Documentation
Level 1 **Initial**	Ad Hoc / Chaotic	CI and TQM Communications

Table I Process Maturity Model

Features in ProcessTOOLS advance shipyard operations through the levels of process maturity toward the Level 5 objective. Enterprise modeling generates the documentation required at Level 2, the flow charts and process maps required at Level 3, and the simulation-capable models required at Level 5. These models also drive scheduling and enactment, and they are archived as artifacts that can be reused on identical or nearly identical processes. Simulation can test out candidate plans to help decide on the best alternative. As processes are simulated or enacted, they generate audit trails. The audit trails can be mined for the statistical process information needed to achieve Level 4 and for the actual performance data needed at Level 5 as feedback to make the models more realistic.

Navy ship repair activities can be divided into two major segments:

- Planning and Estimating, and
- Production.

The Planning and Estimating segment is triggered when the Navy issues a request for proposal (RFP). A shipyard prepares an estimate based on the job specification and submits a bid from the estimate and complex pricing considerations. The Production segment is kicked off only if a shipyard is awarded the contract. The shipyard performs the contract and delivers the repaired ship. Project schedules and costs are recorded during the performance of the contract, but not much of this is used in preparing subsequent bids. The bidding process relies heavily on the experience of senior shipyard management.

The method for evolving ship repair processes to maturity Level 5 is shown in Figure 1. For repair operations, the strategy is to close the estimate-to-production loop by feeding back the actual labor/material cost and schedule to compare to the original basis of estimate. This results in a more accurate basis of future estimates, better cost control, and predictability.

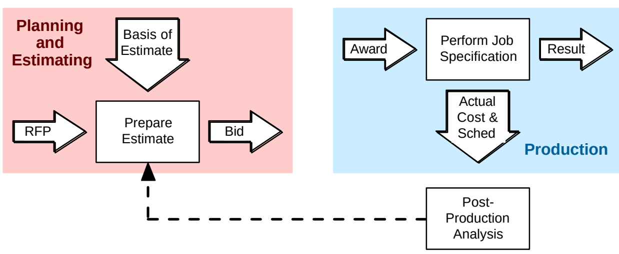

Figure 1 Feeding Back Actuals from Production

Agility

In a manufacturing sense, agility is a comprehensive response to the business challenges of profiting from rapidly changing, continually fragmenting, global markets for high-quality, high-performance, customer-configured goods and services[3]. Agility, applied to business practice, has been brought on by today's broader product ranges, shorter model lifetimes, ability to process orders in arbitrary lot sizes, and ability to treat masses of customers as individuals. Agility is replacing the less profitable mass-production system in the most technologically advanced societies. To be agile, a company must be capable of operating profitably in a competitive environment of continually, and unpredictably, changing customer opportunities.

In an agile company, management must move away from centralized power and authority and share responsibility for the success of a company with the other employees. This necessitates adjusting the available resources on a running basis, monitoring progress toward goals in response to personnel performance, evolving opportunities, and changing parameters of marketplace success. ProcessTOOLS enables agile forecasting forward in time under a variety of "what-if" scenarios for strategic and tactical planning purposes. ProcessTOOLS facilitates agile operations by providing real-time status monitoring of ongoing work, rescheduling activities in response to unpredictable changes, and allowing workers at all levels of an enterprise to simultaneously view all of the information relevant to their tasks.

A goal in managing shipyard operations is to locate the right people, the required equipment, and the necessary material in the right place at the right time. This reduces or eliminates many of the problems that contribute to cost overruns and loss of productivity. Excessive costs arise when:

- There is an oversupply or under supply of labor;
- Labor with the proper trade certification is unavailable;
- Equipment either is not available or is available, but not operational;
- Material arrives too early and must be inventoried; or
- Material arrives too late and delays a job.

ProcessTOOLS can be used to plan, schedule, monitor, re-plan, and reschedule shipyard tasks in real-time. The availability of labor and equipment can be scheduled to avoid costly surprises. Material purchases can be planned to synchronize with project schedules in order to avoid costs associated with early and late deliveries.

Testbed Site Selection

Locating the testbed at a relatively small shipyard is best. Introducing changes in direction or focus is much easier in a small shipyard. Equipping a small shipyard with computers is a much lower capital expense than it is for a larger shipyard. In a small shipyard, the chain of command has fewer layers, and all employees have direct knowledge of many facets of the company's operations. Finally at a small shipyard, an individual employee is expected to perform multiple responsibilities and authorities without disrupting operations.

Expected Benefits

ProcessTOOLS provides detailed production schedules by clearly defining processes and sub-processes. This identifies all components of actual work to be accomplished and the order in which it is performed. ProcessTOOLS assigns tasks to resources, defines goals for workers, and allows a manager to view the scheduled tasks and processes in real-time. With the ability to view all scheduled task and resource assignments, management understands the ramifications of changes and is guided in predicting the outcome of alternative scenarios. Customers are informed by up-to-the-minute contract status information. Workforce predictions become more accurate, which minimizes unscheduled work time or over-manning. The reduction of ephemeral paper reports through interaction with real-time information is a large benefit to the shipyard and their customers.

PROCESSTOOLS OVERVIEW

This section describes the current functionality and architecture of ProcessTOOLS.

ProcessTOOLS Functionality

The relevant functional capabilities of ProcessTOOLS are: modeling, scheduling, simulation, forecasting, enactment, and analysis.

Enterprise Modeling. ProcessTOOLS modeling capability is designed with novice users in mind, providing simple, easy-to-understand interfaces. Specialized editors have been implemented to make model building as straightforward as possible. The user is able to focus on the model, rather than the details of the tool.

Scheduling. In most organizations, scheduling resources to perform process steps is an important task. In organizations that produce small lots of special orders, scheduling becomes a critical procedure, and efficient scheduling is necessary to minimize work-in-progress. ProcessTOOLS supports an advanced scheduling package that can use a variety of algorithms, such as “just-in-time” or “soonest,” to assign resources to process steps at particular times. Table II identifies the algorithms currently available for use in the scheduling process.

generated schedule. The MANAGER component monitors the schedule and sends messages to resources when a process is due to be executed. Special distributed components called AGENTs are associated with resources. AGENTs provide interfaces to human operators, computers, and machines, and are used to display task lists and send back status messages that are used to update a real-time display. Moreover, during enactment, ProcessTOOLS automatically gathers statistics about resources and processes that can be used to tune models and update

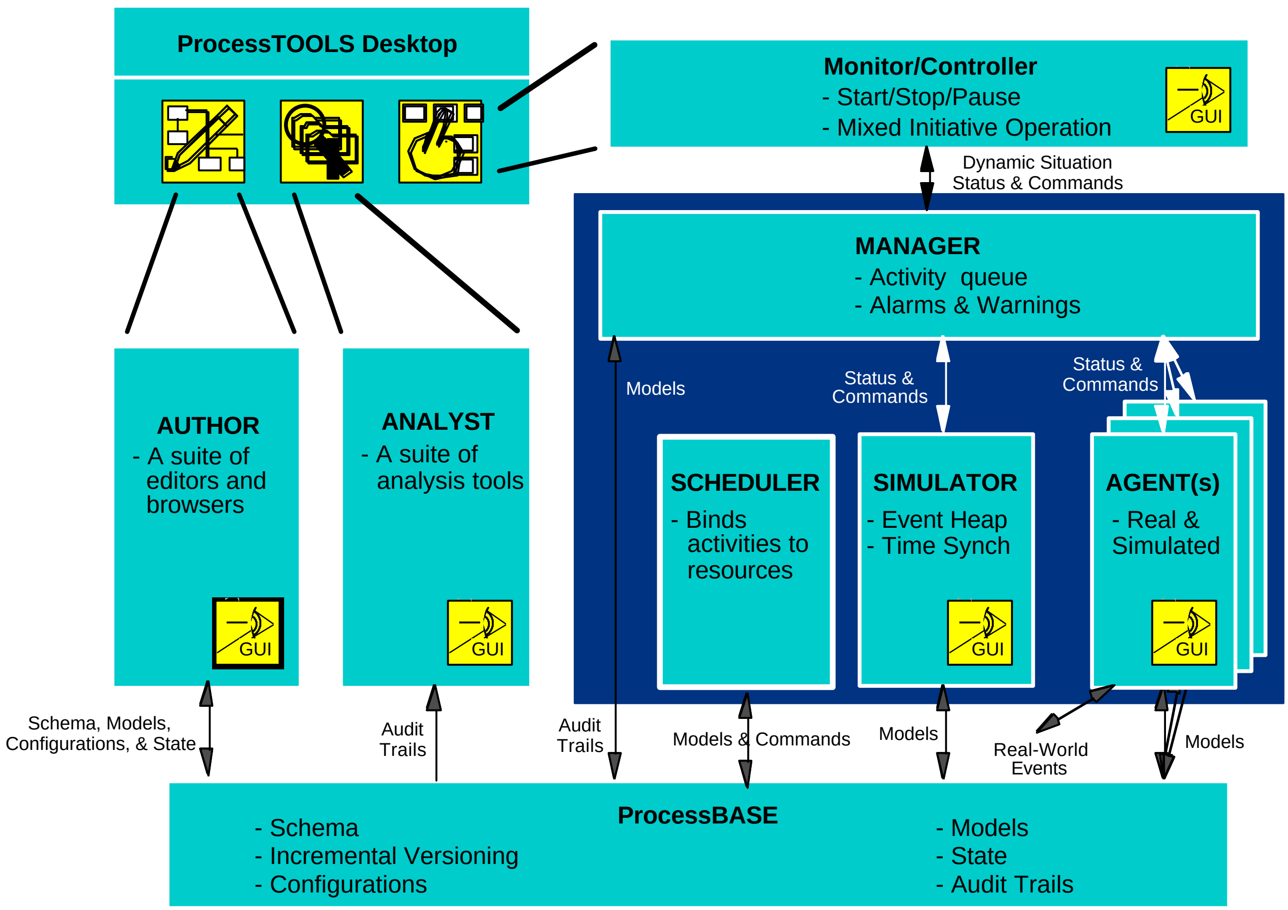

Figure 2 ProcessTOOLS Architecture

Resources are not embedded into the process description. Instead, ProcessTOOLS supports the late-binding of resources so that the assignment of particular resources to process steps can be made when the steps are scheduled.

Simulation and Forecasting. The enterprise models built using ProcessTOOLS can imitate the operation of an enterprise by running them in a discrete event simulation. Simulation can be used to determine whether a certain order can be completed with the stated delivery date or to investigate the effects of adding another resource. With ProcessTOOLS, a manager can apply the same models that are being used to enact the enterprise to run projections and answer “What-if” questions.

Enactment. ProcessTOOLS can be used to automatically manage the enactment of processes according to the

parameters for simulation.

In shipyard enactment, foremen and supervisors operate the computer on behalf of workers. AGENTs incorporate interfaces to allow them to operate as local internet applications or as World Wide Web clients, using Web browsers.

Performance Data Analysis. ProcessTOOLS generates enterprise performance data which can be evaluated for performance. Enterprise metrics are

Scheduling Algorithm	Description
Just-in-Time	Schedule all tasks to complete at latest possible date while meeting delivery time.
Slack	Schedule task starting now, ending just before the job is done.
Soonest	Schedule task starting now, and every new step to start as soon as possible.

Table II Scheduling Algorithms

measures of characteristics or performance of enterprise entities or activities. The purpose for obtaining metrics is to manage, or better manage, the enterprise. Hence, the process of collecting metrics to better manage an enterprise consists of the following steps:

- Measure enterprise performance,
- Hypothesize likely areas of enterprise performance improvement,
- Obtain more focused enterprise performance measures,
- Devise and introduce likely effective process improvements, and
- Re-measure process performance and statistically test for significance.

The above steps are repeated continuously and in a variety of contexts throughout the enterprise, given that once the greatest local process impediment is removed, another always stands in wait as the next "long pole."

The enterprise model information view contains a number of sub-components in which metrics can be readily gathered (due to the electronic format of the contained data).

ProcessTOOLS Architecture

While research and commercial tools exist that can perform one or more of the modeling, scheduling, enactment, and simulation functions, ProcessTOOLS is unique in that all the functions are integrated into a single package and utilize a common representation. The major components of the ProcessTOOLS architecture and their interrelationships are shown in Figure 2. Depending on processing requirements, the system can be configured so that all of the components execute on one processor, or they can be distributed as required across a network of processors. Individual components are described in more detail below.

AUTHOR. A critical component of enterprise modeling is the capability to model processes. The AUTHOR component contains a graphical programming language for modeling processes. Processes can be modeled as collections of steps connected by links representing sequencing, and flow/control constructs representing conditionals, loops, and other composites. The diagrams are constructed using a drag-and-drop interface, and modeling is guided by special editors associated with each construct.

Monitor/Controller. Using the Monitor/Controller, a manager can detect at a glance the status of active processes within an organization. Figure 3 shows what a manager may see using Monitor/Controller.

The display contains boxes that represent process steps, arranged in chronological order according to the current schedule. The dotted vertical line near the middle of the display is the now line - boxes to the left of the now line have completed execution, while those to the right have yet to start. The boxes are color coded according to task status. A box can be selected and expanded in an additional display to provide more detail.

MANAGER. MANAGER is a dispatcher that

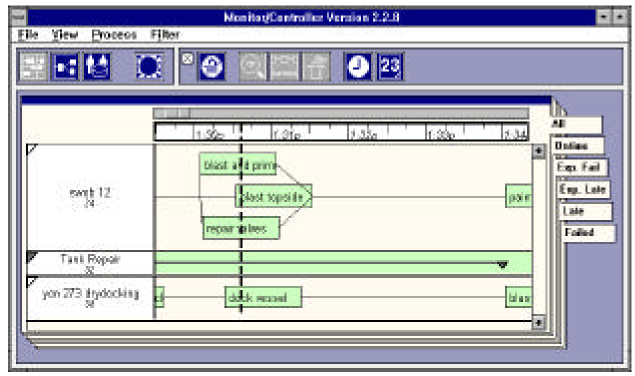

Figure 3 Monitor/Controller View

controls enactment or simulation, and it records data for all events. This provides a project manager, shop superintendent or foreman a review of the current job task list. By using MANAGER, the foreman is notified continually of worker tasks and has the ability to assign workers to a task. The foreman provides status changes to AGENTs like task start, pause, continuation, various required task inputs (values, conditions), and task completion (successful or unsuccessful, with optional explanations).

SCHEDULER. SCHEDULER is a scheduling algorithm that assigns a start time and finish time to each process step based on precedence order. Additionally, SCHEDULER dynamically binds resources to each process step by matching the process step's requirements to the resources' capabilities.

SIMULATOR. SIMULATOR is a generator of simulated events that substitute for enacted events. A simulated statistical variation generates confidence in completing work as scheduled. Also it provides an estimate of future manpower utilization, task durations, and job cost. The simulation allows "What-if" explorations, such as the effects of changing subcontractor mark-up cost, using shift labor, and procuring equipment. Simulation accountability is based on past performance or equipment failure rate and repair times. The shipyard can use these results to increase bid accuracy, or schedule to mitigate performance risks.

AGENTs. AGENTs are a distributed, web-based computer interface to human operators. This interface shows a worker's list of scheduled tasks when a worker pulls up the day's assigned tasks.. Figure 4 shows what a user would view on an agent interface.

ProcessBASE. ProcessBASE is an object-oriented, persistent data facility which stores all transactions for later use. AUTHOR uses ProcessBASE to store models; MANAGER stores the audit trail structures required by ANALYST for analysis.

ANALYST. Using the process and resource

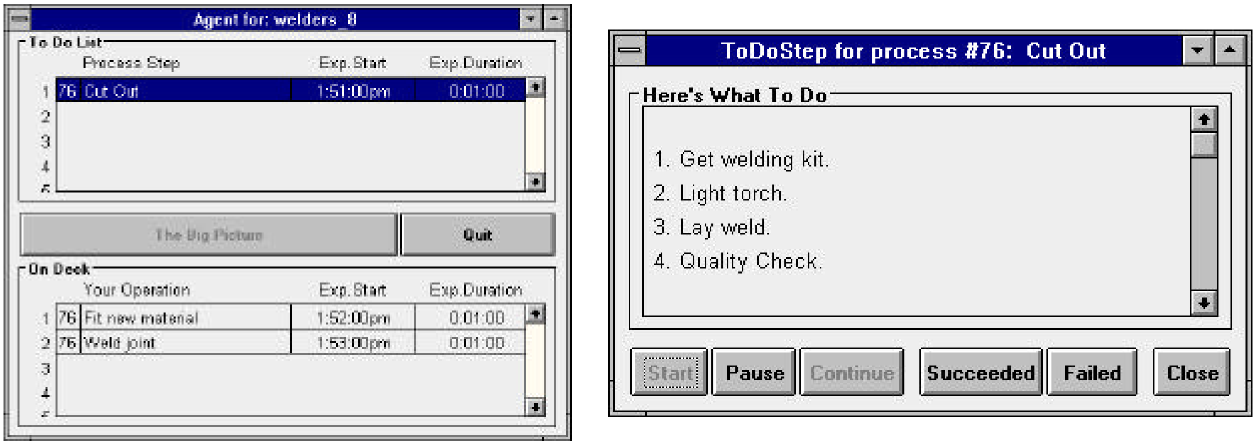

Figure 4 Agent View

models to enact or simulate an organization's business provides a wealth of information, which is archived by MANAGER in audit trails. MANAGER collects statistics (e.g., actual start and end times, actual cost, and actual resource assignments) for each process and process step. This information forms the basis for the performance analysis of actual operations computed and displayed by ANALYST. and actual resource assignments) for each process and process step. This information forms the basis for the performance analysis of actual operations computed and displayed by ANALYST.

USERS IN A SHIPYARD ORGANIZATION

ProcessTOOLS is targeted for use by many different people fulfilling roles at all levels of a shipyard organization. The abstract shipyard organization of Figure 5 is not that of any specific shipyard, but it is intended to provide the context for illustrating the use of ProcessTOOLS in performing various tasks. This section describes typical users and shows how they would use the ProcessTOOLS suite as a job flows from bid, through performance, to contract completion. The target users include the CEO/general manager, project manager, superintendent/foreman, and quality assurance manager.

CEO/General Manager

The CEO and general manager are responsible for bid/no-bid decisions, management of the in-flow of new work, and oversight of current jobs. Such individuals use ProcessTOOLS to model and simulate the shipyard's ability to profitably perform a particular job mix on time when constrained by available resources. New work arrives for consideration in the form of a Request for Proposal (RFP), Supplemental Agreement (shipyard initiated change to contract), or Change Order (customer

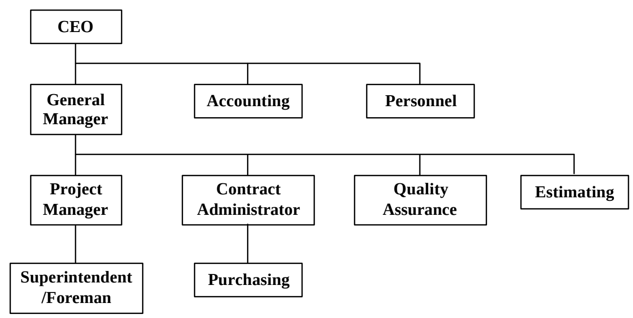

Figure 5 Typical Shipyard Organization

initiated change to contract), with work specifications, including start and completion dates. New work is modeled, which includes the process steps to be performed and the capabilities required to perform them. The model is run (starting at the time of the proposed new work) in a simulation with process models of current production jobs and anticipated available resources to forecast the completion date and provide a level of confidence in that date. Confidence in the completion date is strengthened and the plan is improved by "what-if" simulation of the impacts of adding or removing resources, subcontracting work vs. bringing work in-house, and other trade-offs. The benefits to the CEO and general manager are:

- Confidence in meeting job requirements under a variety of circumstances,
- Labor and material estimates for contract performance, and
- A tentative job schedule before the bid is submitted.

Project Manager

The project manager is directly responsible for a specific project, seeing that all of the work is completed according to specification and scheduled delivery dates and within budget. Once a job is bid and won, the project manager adopts the job model, which was created during the bidding process, as the baseline for performance. The new job model is scheduled with the current job mix and shipyard state, and a simulation is rerun to confirm milestone date feasibility. Then the new job model is enacted with the current job mix to join the real-time model of

shipyard operations. The ProcessTOOLS Monitor/Controller is the project manager's primary interface for viewing real-time project status via several views. The color-coded Gantt view is used in viewing the schedule status and sequence of tasks. The resource view shows the tasks mapped to each resource over time, and the author view shows all of the process diagram's conditionals and branches. The project manager can inspect a task's scheduled start, scheduled duration, actual start, actual duration, and assigned resource. The Monitor/Controller interface can be customized extensively to filter out unwanted items and only show the items of most interest, e.g., the off-schedule tasks appearing yellow or red in the Gantt view, depending on severity. The project manager can use ProcessTOOLS as a decision aid by taking a snapshot of the current state and running simulations based on alternative corrective action to be taken. These simulations provide new delivery dates and confidence measures, which the project manager can use in making decisions on which alternative corrective action to take. Tasks can be rescheduled using different objectives (slack, just-in-time, etc.) and resources can be added or subtracted (including subcontractors). ProcessTOOLS also provides up-to-the-minute status for customer inquiries. The benefits to the project manager are:

- Capability to re-plan under changing and unanticipated circumstances,
- Ability to test and compare alternative plans by simulation,
- Sustained confidence in on-time completion,
- Maintained labor and material estimates to complete the contract, and
- A continually updated job schedule.

Superintendent/Foreman

The superintendents and foremen are those individuals who directly oversee the performance of trade-specific production tasks, lead groups of tradespeople (e.g., welders, sandblast/painters, machinists, and riggers), and report to the project managers. During enactment, tradespeople are given instructions via "To-Do" and "On-Deck" task lists. Responsible superintendents and foremen provide real-time status on behalf of the tradespeople they represent by notifying ProcessTOOLS when tasks start, complete, pause, continue, and fail. Tasks are completed either successfully or unsuccessfully (with an available explanation facility). In addition to tracking tasks in real-time, superintendents and foremen also may use the modeling and simulation capabilities of ProcessTOOLS to support operational decision making, but the focus is shifted to a specific trade across all projects at a lower operational level than a project manager. Status of multiple projects is reviewed at the task level from multiple perspectives:

- Schedule status and task sequence with the Gantt view,
- Resource assignment with resource view; and
- Task control flow with the author view.

In response to performance problems, a task can be assigned another resource or rescheduling can be recommended. The benefits to superintendents and foremen are:

- More accurate labor and material estimates to complete assigned tasks,
- Better forecast labor requirements,
- Rapid distribution of task synchronization and status, and
- Reduced status reporting.

Quality Assurance Manager

The quality assurance (QA) manager is responsible for the compliance of quality standards for all work performed at a shipyard. The authoring capability of ProcessTOOLS enables the QA manager to review process diagrams for control requirements, which can include required process control procedures (PCPs), training requirements, and certification requirements. This maintains confidence that the proper procedures are being utilized. During enactment, the QA manager reviews processes for proper sequence and resource assignments as well as monitoring and maintaining worker qualifications. The QA manager is able to establish a predictability in end product quality and increase accuracy of performance records through greater control of the processes. The benefits to the quality assurance manager are:

- Confidence that the proper procedures are being used,
- Accountability for accomplished work,
- Greater predictability of end product quality through greater process control, and
- Increased accuracy of performance records.

SUMMARY

The Maritech Program supports advanced technology development projects that will demonstrate improved practices and processes used for the design and construction of ships in the United States, surpass international competition, and yield significantly more affordable Navy ships. DARPA's Agile Manufacturing Program has sponsored the development of a prototype suite of software tools, called ProcessTOOLS, for use in modeling and managing enterprises. Using ProcessTOOLS, a shipyard can maintain an accurate model of its operations, utilize advanced scheduling techniques to assign process steps to shipyard resources, manage the execution of processes according to schedule, accurately monitor the status of processes in real-time, and simulate the shipyard forward in time from its current state to assess the impacts of a contract award, to forecast the effects of changes in internal processes, and to evaluate the probable delivery date of an order. By modeling a repair or construction job prior to bidding, ProcessTOOLS facilitates more detailed planning during estimation, which results in a more realistic bid. By providing continually updated status during production, ProcessTOOLS expedites timely delivery of labor, material, and equipment to the job when it's actually needed. Event information is archived as it happens during production to form a rich source for accurately measuring performance and realistically supporting future estimates.

ACKNOWLEDGMENTS

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Modular Outfitting

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ABSTRACT

The concept of modular construction is not new in the manufacturing, construction, automotive , aeronautical or marine industries. This concept is presented from the initial stages of design ,and production, through ship builder s trials and operations. Through careful thought, engineering, and communications with all involved, from design, construction, and operation ensure a quality product with schedule reduction using modular outfitting. Each phase of modular outfitting is discussed to explain how it has effected, organizational issues, design issues, financial issues, production issues and life cycle or operational issues.

INTRODUCTION

Shipbuilders have become extremely competitive in the world market over the past 20 years. This has forced the ones who wish to remain in the business to continually improve designs, and production strategies. Thyssen Nordseewerke in Emden Germany has been faced not only with this external challenge but with internal constraints for a number of years and has developed a patented concept for modular construction of its engine rooms (see Figure 1).

This approach has provided the ship builder with a number of benefits and also some concerns. The major benefit has been schedule reduction on the slip-ways, on the order of 15 weeks. Quality of, and repeatability of units and modules have been positive, and training of apprentice workers more efficient. Organizational communications from all levels of the yard have seen positive improvements. Managerial measurements on performance and cost issues are now simpler to implement and perform. Another key area of improvement due to modular construction is the overall man hours per ship have consistently come down.

However there have been a number of teething problems. Two of the most pronounced problems are due to cost increases associated to initial design and production.

Costs of design increased as a result of the level of detail required for production and also from a higher level of complexity of primary and secondary structure of and within the units. The increased costs are also associated to the ship structure or the “nacelle” required to hold the units.

Production costs also increased due to the requirement for a new production factory and the transportation equipment required to move the engine room to the construction ways.

In the area of operations, the owners concerns for maintenance and obstructions due to the increased structural elements were addressed early in the design phase and a few were also corrected after a number of ships were produced. Early ships also experienced some vibration problems. Specific solutions, such as a hydrodynamic damping tank above the propeller, and attachment of the stack to the house, have virtually eliminated these past vibration problems.

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United States Patent [19]

Wilts

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[45] Date of Patent: Apr. 5, 1994

[54] SHIP, IN PARTICULAR MERCHANT SHIP

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[52] U.S. Cl. .... 114/56; 114/77 R

[58] Field of Search .... 114/56, 65 R, 72, 73, 114/77 R

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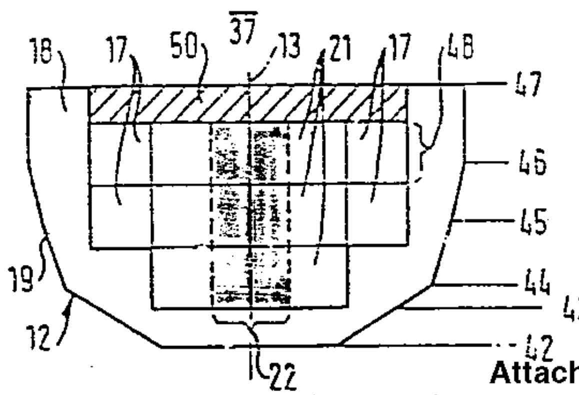
Attorney, Agent, or Firm—Nils H. Ljungman & Associates

[57] ABSTRACT

Ship, in particular merchant ship, with at least one large power plant such as a main propulsion engine (11) located in the ship's steel hull, around which there are the necessary auxiliary spaces, such as access spaces, bunkers, tanks, compartments, control rooms, workshops, control devices, distribution centers, pumps, hydraulic power plants, etc., characterized by the fact that the ship's hull (12), in the vicinity of the main power plant (11), has a nacelle (20) which is open on top, which is designed so that it becomes wider in steps from bottom to top and/or in the longitudinal direction of the ship (13), and is preferably free of bulkheads and platforms, that the height, length and width of the stepped walls (14, 15, 16) next to or under the main power plant (11) are of a specified modular dimension on the order of several meters, in particular 3 m, in at least one dimension, in particular the height, but preferably in two dimensions, and particularly preferably in all three dimensions, and at least a significant portion of the auxiliary spaces are located in rectangular containers or container frames (17, 21, 25) located next to, forward and/or aft of the main power plant (11) or on the stepped walls (14, 15, 16).

12 Claims, 17 Drawing Sheets



Attachment 14

Figure 1. United States Patent # 5,299,520

MODULARIZED ENGINE ROOM

Merchant shipbuilding in Germany is subjected to an ever increasing competitive pressure by Asian and East European shipyards. Therefore, each company is forced to develop massive cost reduction measures. Besides respective strategic and organizational measures, possible improvement potential in the sphere of direct production costs must be utilized. After having given attention to the cost reduction possibilities on the steel construction side, the shipyard has concentrated specifically on the reduction of the time-versus space relationship and the dependency of engine room outfitting on ship block assembly at the slip way. This consideration led to the modularization of large engine room sections into functional modules. Further the modular technology supports the shipyard target in saving man-hours. Consequently the overall production costs have been decreased. These activities reduced the cost of the total vessel by about 30 percent.

The main contributors to achieving this were as follows:

- Building series of ships,
- Purchasing equipment and material in cooperation with other shipyards,
- Concurrent engineering with vendors,
- Value analysis of the design material and the limitation of the design drawings to the absolute minimum necessary,
- More subcontracting to non-shipyard expertise areas,
- Pre-outfitting,
- Standardization, and
- Modularization.

Customary Pre-outfitting

During the building of a vessel, the dependency of ship sections on outfitting often exists and has an important impact on construction times and production hours. The desired high degree of outfitting requires that ship sections remain in the outfitting areas for a longer period of time. Converting this to local schedule change often leads to a disturbance in the global schedule. A common bad practice in the development of proper scheduling for modular outfitting was that sections were delivered without pre-outfitting. As a result of this, an increase in the number of production hours were experienced. Another reason is that shipyard crane capacity limits pre-outfitting, therefore the weight of the ship section is also limited by existing crane capacity.

Advantage of Modularization

The biggest advantage of modularization is proven by the separation of the construction area and time between shipbuilding and outfitting activities. It is very important that early in the project phase it must be determined what areas of the ship can be modularized. This results in the development of engine room modules whose interfaces are clearly defined. This is in order to allow independent construction between shipbuilding, the engine room module outfitting, arrangement of the functional modules and further outfitting within the machinery space. This allows independent production activities with minimum interference to other shipbuilding activities. As a result, only on the slip-way do the engine space modules meet with the ship hull.

This independence has the following advantages:

- Parallel design of shipbuilding and outfitting,
- Parallel production of shipbuilding and outfitting,
- Less disturbance in ship's hull production,
- Less slip-way time,
- Comfortable and faster outfitting of modules in hull,
- Reduction of transportation time,
- Easier to subcontract from cost effective suppliers,
- Reduction of construction time due to standard modules and arrangements, and
- Easier work in nonmodularized area in the empty engine room.

As a practical result the erection of the engine room at the slip-way consists of two space modules, port and starboard, and the main engine and three smaller modules in front of the main engine between it and the forward engine room bulkhead. The erection of the engine room modules within the ship is accomplished within two days.

Modularization Applications

Between 1991 and 1996 thirteen hulls were built in series with modular engine rooms (hull numbers 501-513).

The engine room area was determined to account for 40 percent of the production hours and ship cost. It was therefore determined that standardization and modularization of the ship would yield the most benefits within this space.

In 1991 with the series (starting with hull 501) of 1500 TEU container ships the shipyard decided to replace piping and pump groups by completely assembled and preoutfitted functional modules as follows:

- Low temperature cooling water module,
- High temperature cooling water module,
- Sea water cooling module,
- Separator module,
- Lubricating oil module,
- Fuel oil module, and
- Starting air and control air module.

In the past the dependency of production on installing a large number of individual function units that were difficult to install has been replaced by a much more manageable number of modules on this series of ships. The final outfitting of some functional modules, including generator and air compressor flats is still done on the ship.

The two individual space modules (port and starboard sides) consist of a frame structure where all equipment is tight (bolted and welded), piped to, and wired with the other individual units. These individual units are stacked into two large space modules, comprised of 8 individual units per port and starboard side. This effort is completed within the engine room factory. These two large space modules fit within the engine room, one on the port and one on the starboard side of the main engine . The maximum total weight of each engine

room space module (8 per space module) is approximately 80 tonnes (88.19short tons). The individual module unit dimensions are 12m x 6m x 6m (39.37ft x 19.69ft x 19.69ft). The large space modules contain 60 percent of the engine room machinery equipment. Again there are currently 8 individual module units per ship side (port/Starboard) and 3 in front of the Main Engine giving a total of 19 individual module units.

DEVELOPMENT OF HANDY SIZE 1700 TEU CONTAINER SHIP. (see Figure 2)

This concept of modular outfitting is not restricted to one series of vessels but can be expanded to other larger and smaller series of ships. Not only is the engine room optimized for modular construction but other areas of the ship have also been selected for this type of construction and is discussed below with respect to costs and technical design effort.

The analysis of the building cost (see Figure 3) forced the shipyard to the conclusion that the vessels need to be divided into four major construction blocks.

- Deckhouse,
- Bow,
- Mid-body, and
- Engine Room.

Shipyard goals for this project were as follows:

- The reduction of the total costs by 20 percent or more,
- Reduction of the onboard outfitting by at least 60 percent,
- Significant reduction of time, approximately 30 percent between order and delivery,
- High quality of the product,
- Achieving higher flexibility by creating new methods and standards,
- Reducing manning costs through automation,
- Reducing fuel costs,
- Reducing maintenance costs,
- High endurance,
- High reliability,
- High economic life span,
- Easy repair and upgrading of the main engine, and
- Fast and efficient design process.

A conventional design begins with the lines plan, the steel drawings follow. At this point the detailed engine room drawings can be developed for arrangement of systems and functional units within the engine room, and space allocated for maintenance and operations of the engine room machinery. Construction follows the same pattern. Due to the differences in tolerances between shipbuilding and outfitting, much of the expensive outfitting work typically has been done in late stages of construction on the slip-way and after launching. To shorten the total building time, parallel design and construction are necessary. Therefore, new design methods and construction strategies to replace these conventional methods are needed. The parallel design and construction of engine rooms is only possible when the space for the engine room is defined and the interfaces are simplified. This can be achieved by using a modular design of functional units which have standard dimensions. These functional units must be transportable. This allows the construction, outfitting and testing of the space modules before they are loaded onto the ship in parallel and most importantly, outside of the ships critical path.

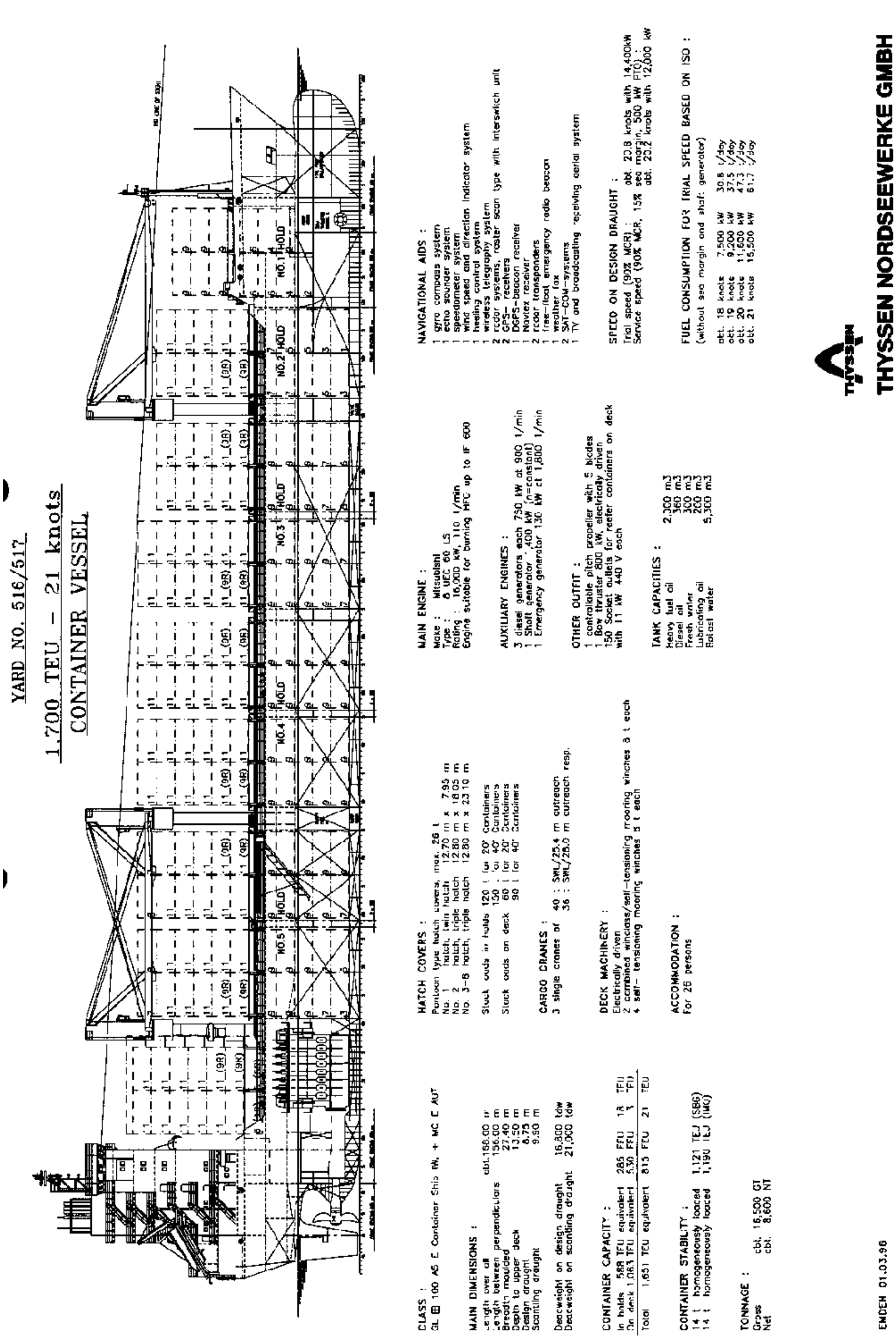
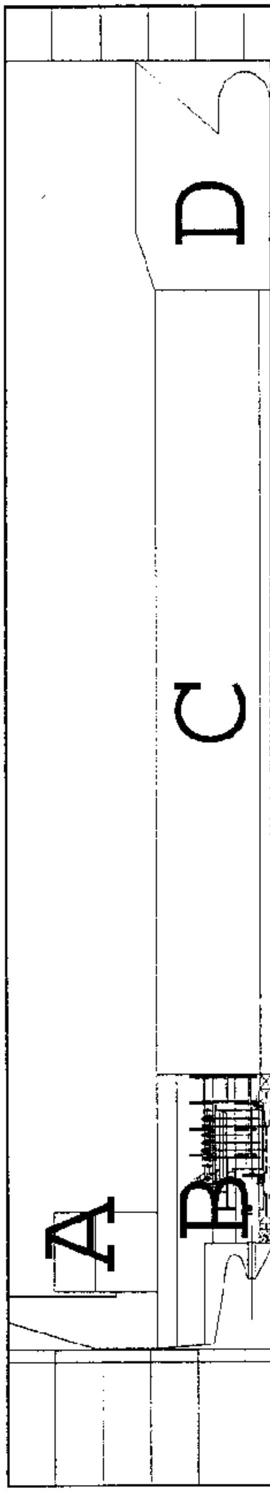


FIGURE 2

Figure 2. 1700 TEU Container Ship

Analysis of Building Costs



	A	B	C	D	
% Steel Cost	7%	27%	57%	9%	100%
% Outfitting Material Cost	30%	58%	7%	5%	100%
% Steel Manhours	15%	33%	32%	20%	100%
% Outfitting Manhours	15%	40%	25%	20%	100%
% Design Manhours	14%	41%	35%	10%	100%
% Total Cost	21%	46%	22%	11%	100%

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Figure 3

Figure 3. Analysis of Building Costs

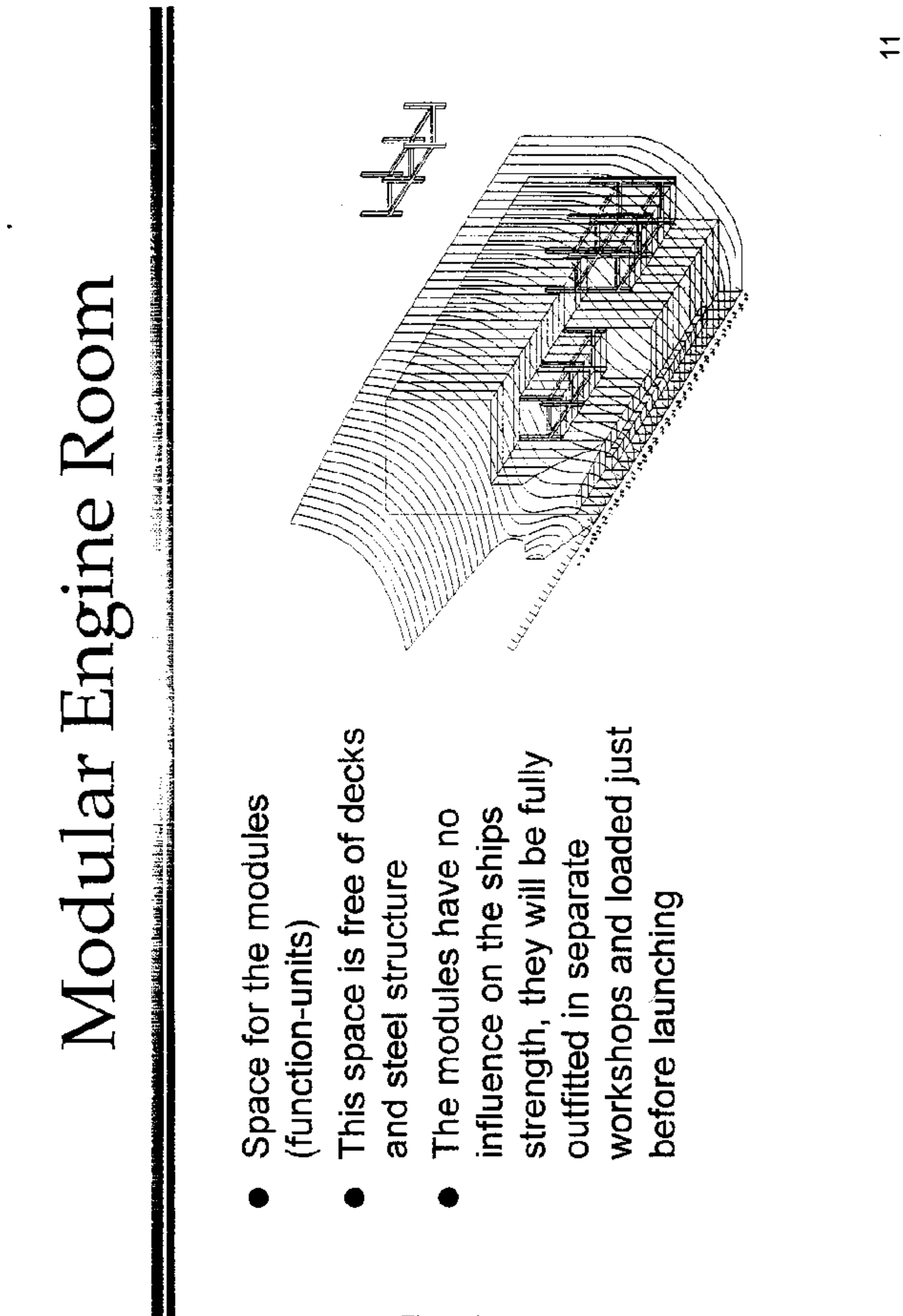

Figure 4

Figure 4. Modular Engine Room

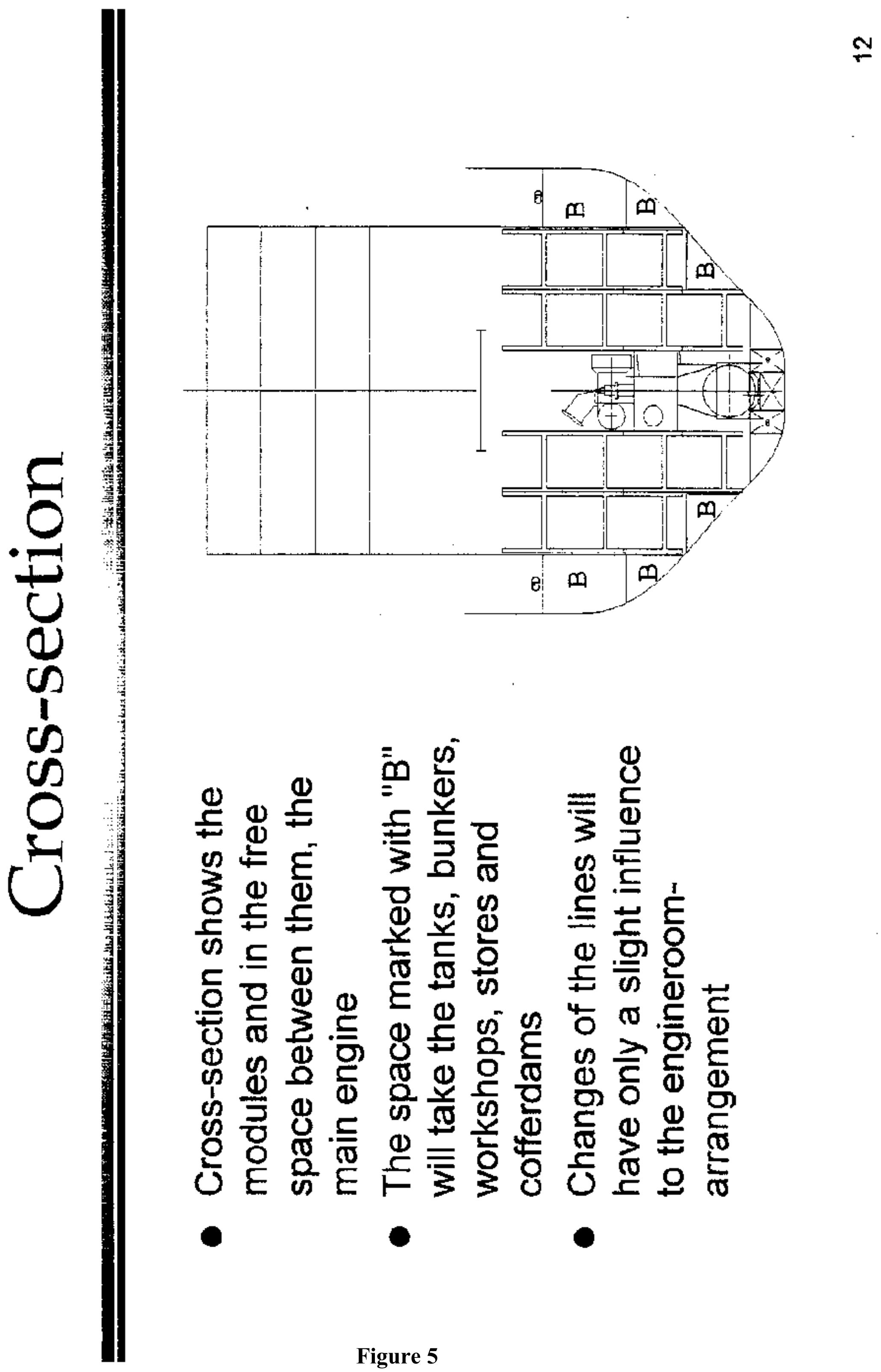

Figure 5

Figure 5. Cross Section of Modular Engine Room

Engine Room Space for the Functional Modules (see Figures 4 &5)

Under this approach the main engine room space on very different types of ships, particularly merchant ships, differ only slightly from one another. For example; the engine room forward bulkhead is generally 3 m from the main engine. The engine room compartment has been designed with vertical and horizontal walls and does not include bulkheads, frames and platforms. The Ship hull or "nacelle" in the engine room area contains usable spaces such as tanks (fuel/water), compartments and the workshop.

Engine Room Equipment

The system engineering group defined the equipment that have the best opportunities to be modularized and locations with respect to other interfacing systems. An example drawing of the HFO fuel system is shown in Figure 6.

The modular standard containers or individual unit modules, with dimensions of 3m x 3m x 6m (9.84ft x 9.84ft x 19.69ft) are connected together in the engine room factory, pre-assembled, pre-outfitted and tested. The space modules (port and starboard) are pre-outfitted outside the ship hull in parallel with the construction of the hull and introduced into the steel hull from the top of the engine room hold. Only the power supply (power, control, sensors) and piping connections to the main engine are installed on board. As a result, the 1700 TEU container ship engine room consists of the following individual unit modules:

- Engine control room,
- High temperature fresh water cooling system,
- Low Temperature Fresh Water cooling System,
- Sea water system consisting of sea water cooling, fire fighting, bilge and ballast pumps,
- Generator sets,
- Integrated ventilation system,
- Sewage system,
- Integrated cable ways,
- Potable water system including evaporator,
- Fuel oil separators included heaters, pumps, and sludge oil tank,
- Refrigeration and air condition system,
- Starting ,working and control air system,
- Integrated fire fighting system, and
- Lube oil system.

The preferred standard dimensions of the engine room individual unit module has been divided into two different spaces in the vertical direction. The upper portion has a height of approx. 2 m (6.56ft) so it can be accessible to standard persons in the 95th percentile range. Pipes, cables and other components are located in the lower part, which can be approximately 80 cm (2.63ft) high.

Foundations for the equipment are suspended and bolted to the frame tubing of the following dimensions, 200mm x 200mm x 10mm (7.87in x 7.87in x .39in).

The design of the engine room space and individual unit modules includes only right angle bars therefore interfaces between them can be predetermined to an accuracy measured in millimeters.

MODULAR SYSTEMS AND STEEL STRUCTURE

All space modules are connected to the hull but are not a part of the ship structure, they are structurally uncoupled. By being structurally uncoupled they are not required for hull stiffness and are separated from main engine, shaft and propeller forced vibrations. The space modules replaced previous engine rooms designed with tween and platform decks. The engine room space is similar to the container ship cargo hold concept. The engine room is a hold for the machinery space modules. The transverse strength of the engine room without tween decks and pillars does not create any problem due to the relatively wide fuel oil wing tanks (see figures 8 & 9) The structure has been designed according to German Lloyd Classification Society (Germanischer Lloyd).

The global vibration behavior of hull and superstructure was investigated using a three dimensional finite element model and the coupling effect between hull and superstructure was investigated. The vibration behavior of the engine room structure without tween decks has been found to be as good as the behavior of previously constructed conventional engine rooms.

Module Support

Similar to the container cargo hold, the engine room is equipped with foundations and horizontal supports for modules (see Figure 10). Due to the shape of the ship's aft body, aft modules can not be mounted directly onto the inner bottom. Special foundation structure is necessary (see Figures 11 & 12). The foundation structure is loaded vertically only. Horizontal supports are arranged according to the unit module decks. In the transverse directions the modules are supported by the ship wing tank structure and in the longitudinal direction by platform decks aft of the modules and the forward engine room bulkhead.

HFO Heater

- The HFO Heaters together with the Pumps, dearator and viscosimat, including all measuring points, the piping and wiring, are mounted together with the separators and sludge tank in one module

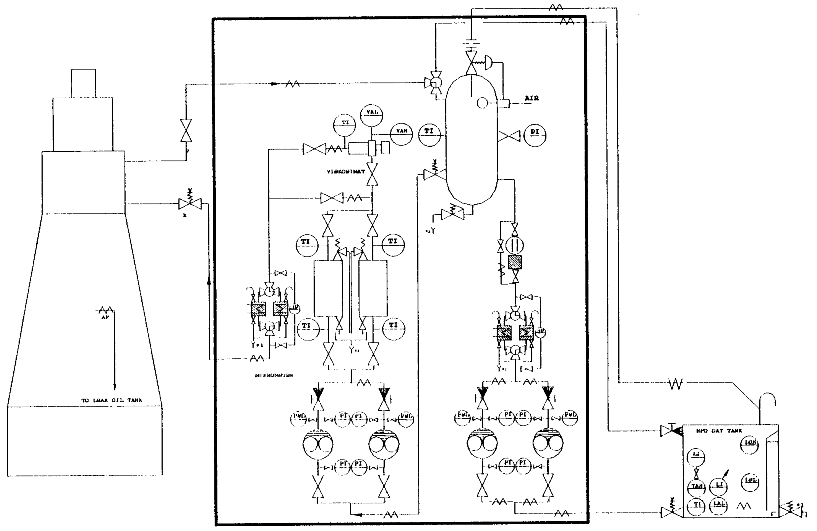

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Figure 6. HFO Heater System

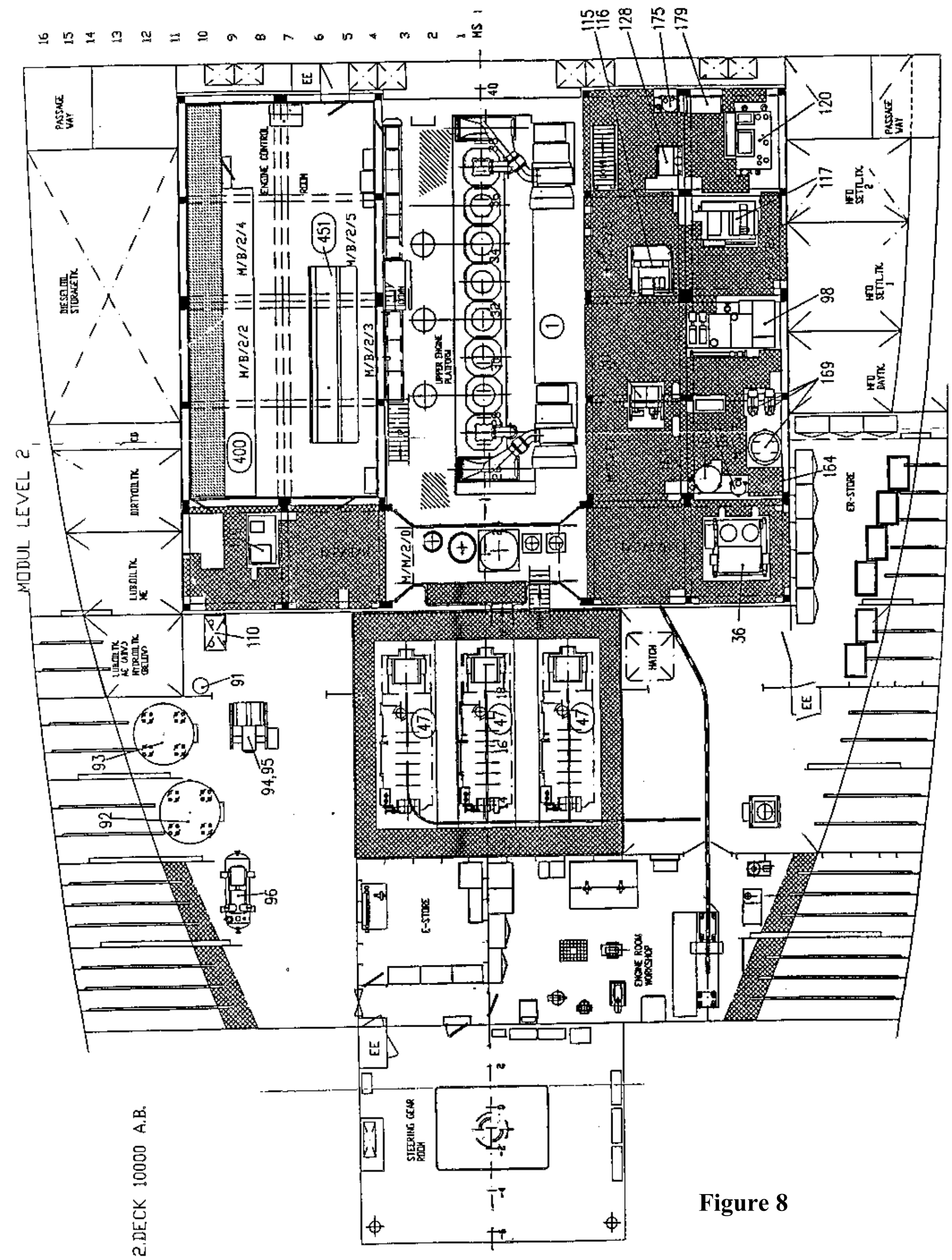


Figure 8. Plan View of Engine Room w/ Wing Tanks

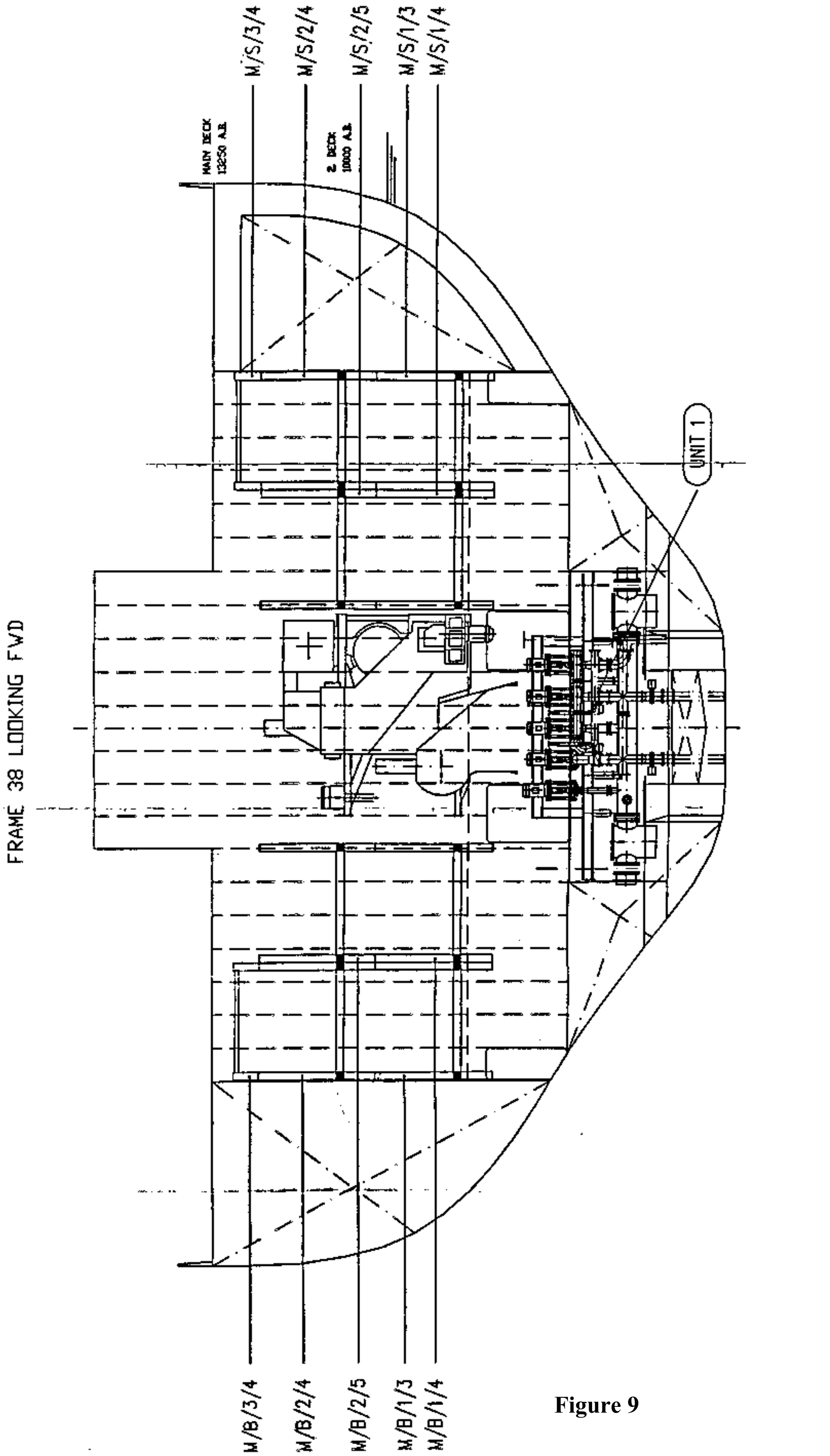


Figure 9

Figure 9. Section View of Engine Room aft Lkg fwd

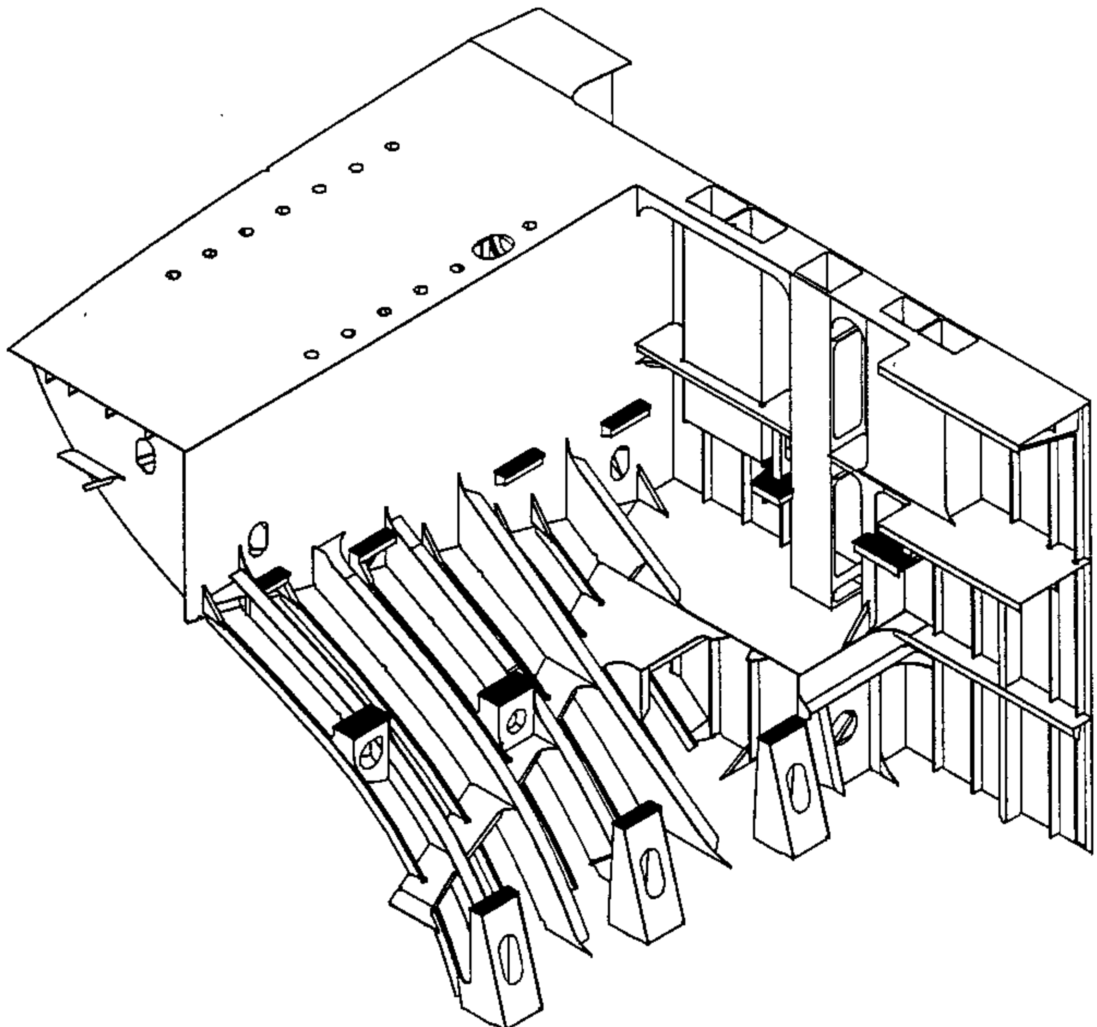


Figure 10

Figure 10. Supports for Modules

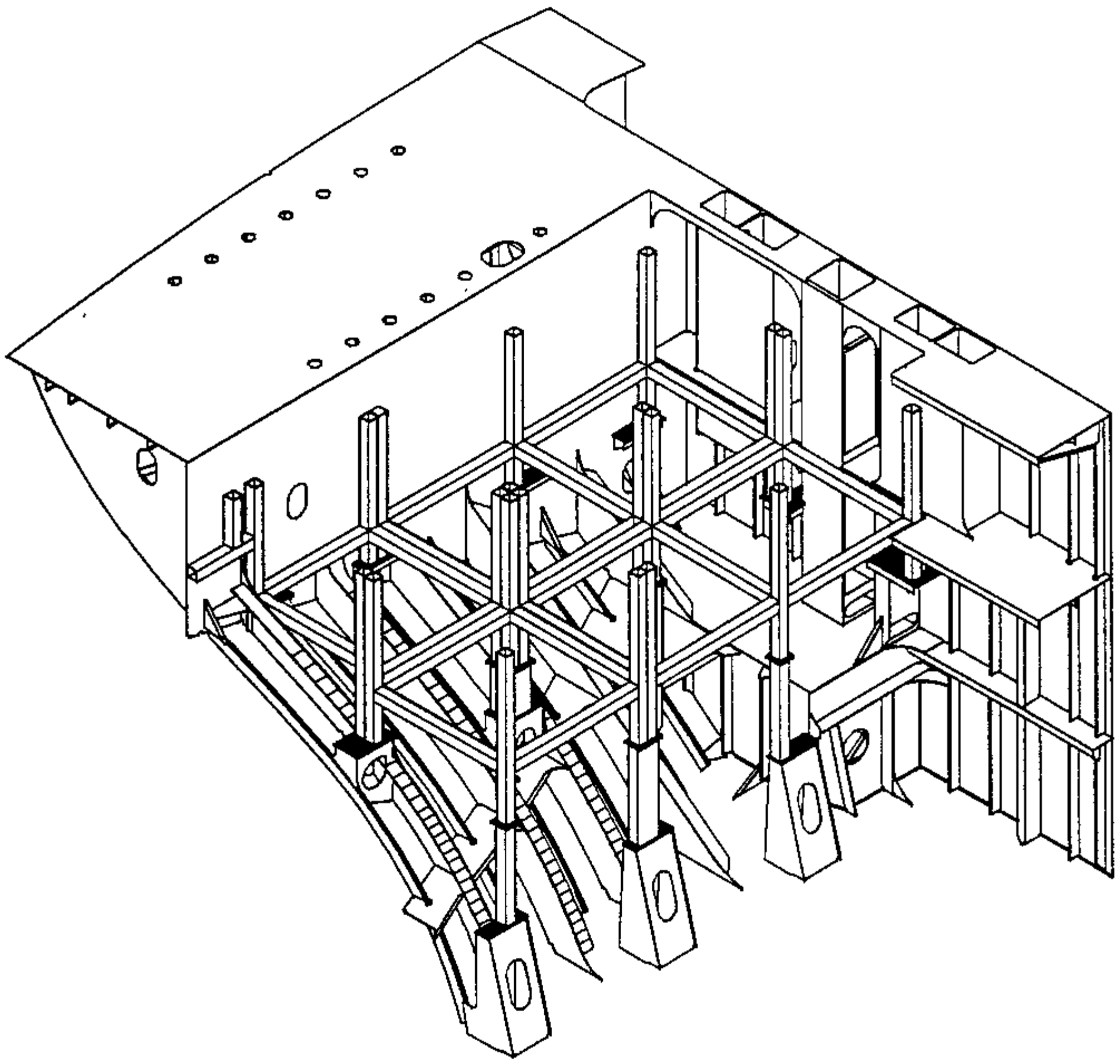


Figure 11

Figure 11. Modules Attached to Foundations

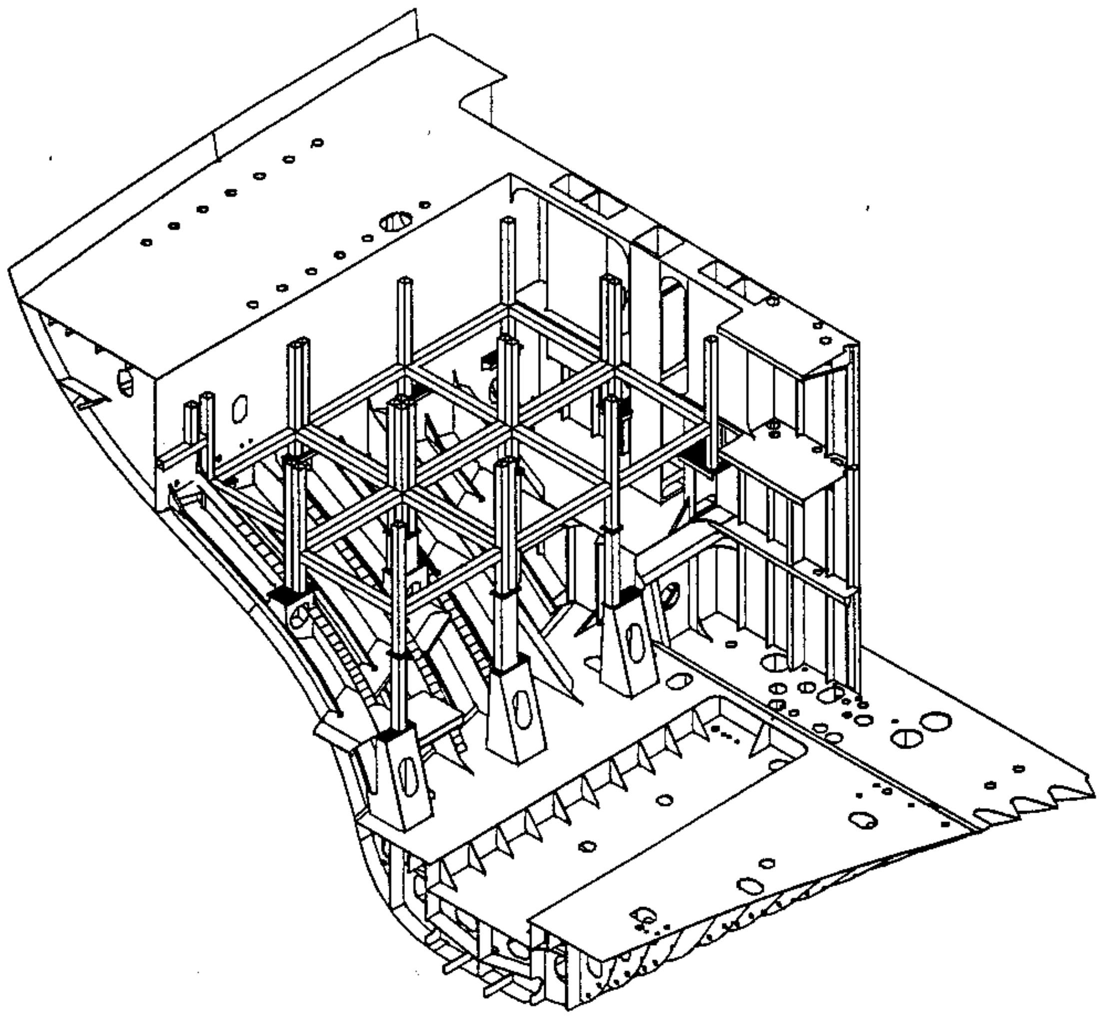


Figure 12

Figure 12. Further Detail of Modules w/ Foundation

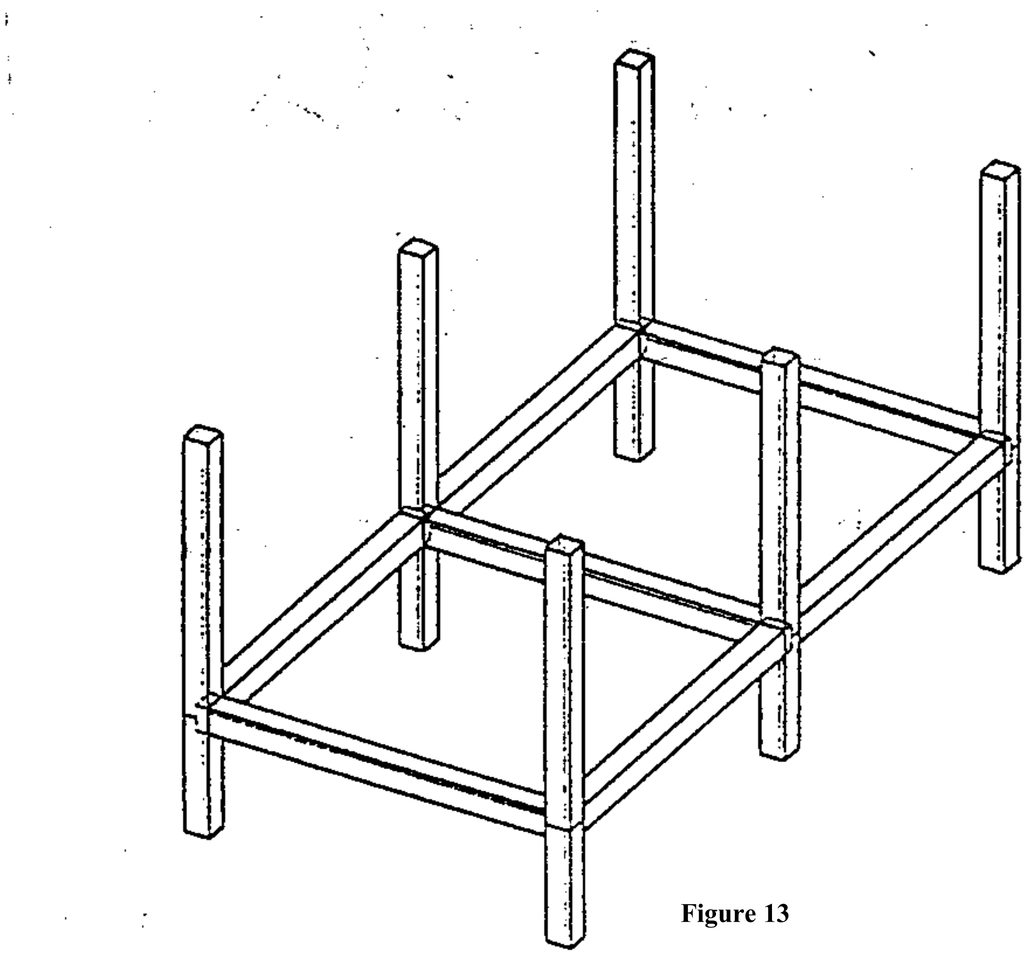


Figure 13

Figure 13. Standard Module Frame

The Frame Type Module (see Figure 13)

The standard module deck consist of open horizontal frame, 6m x 3m (19.69ft x 9.84ft) with two longitudinal and three transversal girders, six support pillars, reaching 2 m (6.56ft) above and 1 m (3.28ft) below the module deck. All structural frames are made of rectangular tubing 200 mm x 200 mm x 10mm(7.87in x 7.87in x .39in).

The maximum module weight as built for shipyard hull numbers 505/510 to 513 was as follows:

Basic frames	2.1 tonnes (2.3 S tons)
Outfit supporting structure	4.2 tonnes (4.6 S tons)
Outfit and equipment	7.7 tonnes (8.5 S tons)
Total	14.0 tonnes (15.4 S tons)

This represents 0.43 tonnes/m2 (0.47 S tons/ft2) equally distributed. The outfit supporting structure is represented by beams and clips that are necessary for nearly all fittings and for walk way platforms.

The Vibration and Strength of the Frame Modules

The static strength of the modules structure was not a problem. However the vibration behavior of the modules structure is a major design factor. The vibration has been investigated carefully, in all cases especially in area of heavy fittings. For example the plate cooler units. The natural frequencies were calculated by means of three dimensional finite element beam models. The models covered the basic frames, additional support beams and masses of the main fitting components.

The excitation frequencies of hull numbers 505/510 to 513 were as follows;

- Propeller first harmonic 6.7 Hz
- Firing of the main engine 11.7 Hz
- Module design frequency 13.0 Hz

Vibration problems did not exist in the structure of the modules.

LESSONS LEARNED

Representatives of the U.S. Navy's Mid Term Sealift Ship Development Program (MTSSDP) Producibility Task made two Product and Process benchmarking trips to Thyssen to investigate the factors that allow this German shipbuilder to be globally competitive and to further understand the benefits and possible weaknesses of modular outfitting. These benchmarking trips were applicable to the Engine Room Arrangement (ERAM) project whose goal is to produce world class ship propulsion machinery design concepts, to the Generic Build Strategy (GBS) project from a design/production standpoint; and to the Product Oriented Design and Construction (PODAC) cost model project.

A major lesson learned was that engineering, design and build processes make up an integral part of each companies strategy for competitive success. Top management at Thyssen was forthcoming in explaining how forecasting, marketing, financing, product development, production and customer support were concurrently planned and executed. Available literature on shipbuilding concentrates on business issues and does not explain how the engineering processes need to be factored in, thus it is important to gain first hand knowledge from the shipyard.

Thyssen is a Naval constructor which fills in the lows of military contracts with commercial work. This is offered as lesson for a number of U.S. shipbuilders who are in a similar situation and would like to smooth the highs and lows of business with different product lines.

The shipyard is counter-balancing their extremely high labor rates with the most producible designs. The focus of the first visit was to understand their patented modular engine room design which almost completely pre-outfits standard sized units that are landed onboard after block erection of the entire ship including the stern. The second visit was made to participate in shipbuilder sea trails and verify operational constraints. We were specifically concerned with possible vibration problems due to the extra primary and secondary structure. This could become a complex "source, path, receiver" relationship for vibrations generated by the propeller, shaft line, and/or main engine.

By the time of our second trip for sea trails, The shipyard had evolved the design concept one step further to be, lighter, more producible, less expensive, and with similar schedule reduction. This latest concept comprises four platform modules, each of which is half of the engine room height and breadth. This new concept will be utilized on their next generation container ship series. This ship a 2500 TEU vessel is shown in figure 14.

Sea trials were two days in the North Sea on hull no. 512, the M/V *San Fernando*. This 1,500 TEU container ship was the 10th in a series using the original smaller engine room modules. A similar modular machinery design by another shipyard from the 1970's resulted in vibration problems to secondary systems such as pumps and electrical panels. Therefore our concern was that the shipyard's engine room design, although highly producible, may be operationally deficient from the machinery vibration standpoint. We independently took vibration measurements which showed that vibration severity numbers, both structure and rotating equipment, were well below classification society and ISO guidelines for a ship in ballast condition.

The ship performed without incident (except the sewage system became overloaded by 50+ people onboard) throughout all trial requirements.

The combination of the slow speed main engine with the controllable pitch (CP) propeller is the most efficient combination for container ships of this type and size. Not only does this combination allow the Main Engine to run at optimal conditions (85-90% MCR) giving the highest efficiency, but the CP propeller gives great flexibility in maneuvering and in running the engine at dock side when testing engine after overhauls, etc. This combination gives benefits such as reduced NOx with engine running under optimal conditions. The ship also utilizes a shaft generator throughout the entire range of the operation profile thus reducing the electric load on the 2 service diesel generators.

The design appeared to adequately address the area of human factors and ergonomics. Operations and maintenance issues have been thought through with adequate lighting, overhead cranes and chain falls, good ventilation and good ingress and egress routes for both humans and equipment. The machinery space was open and was not interfered by the modules and unit frames.

CONCLUSIONS

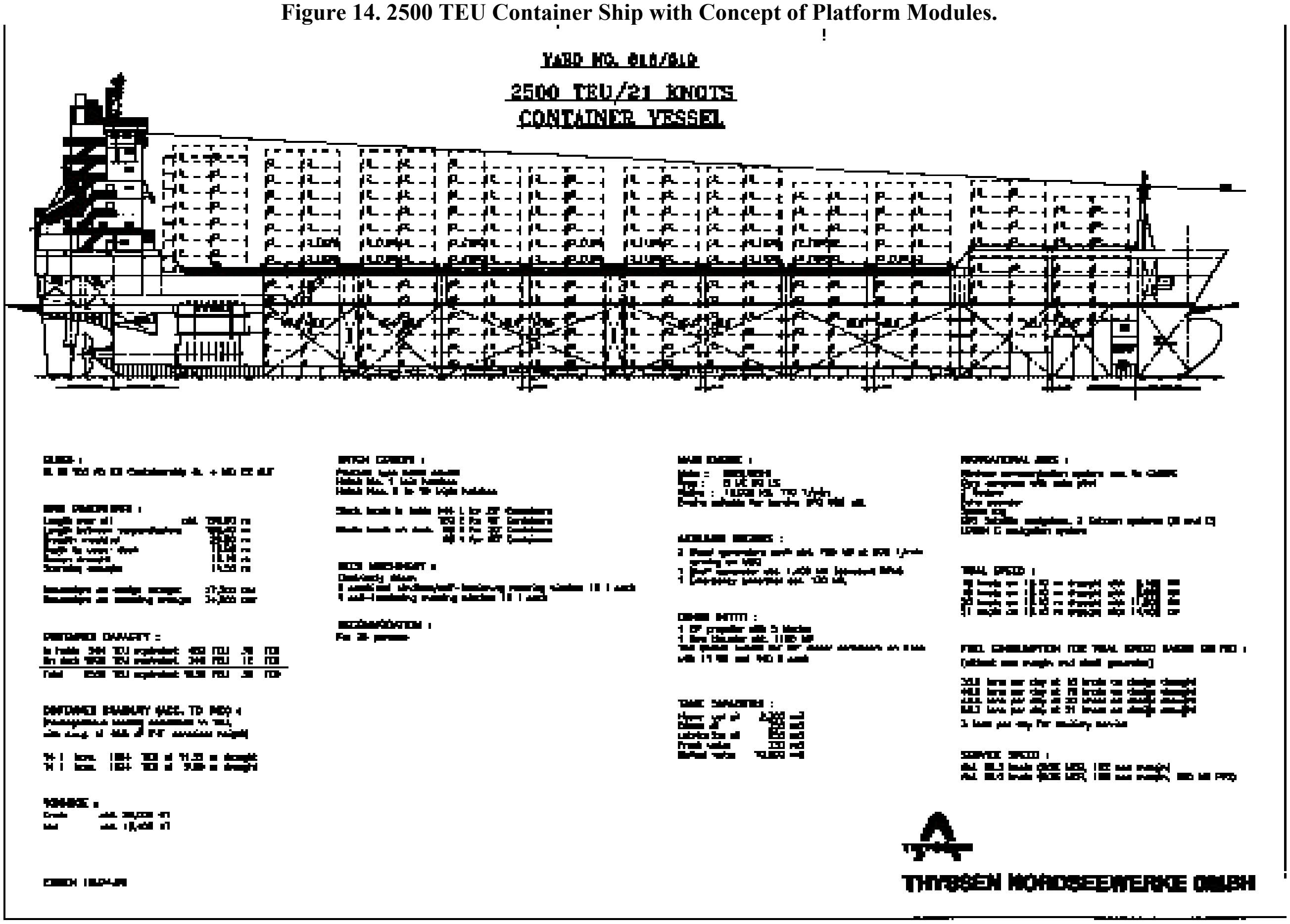
The shipyard part of Thyssen group and a subsidiary of Budd Industry USA can be used as an example of a model for US Shipyards in transition. This transition from a total government or Navy economy to a combination of market and government economy due to diversify work can be a product balance that not only meets the Military needs but those of the Maritime industry as a whole. The shipyard's approach of 1/3 military, 1/3 commercial, and 1/3 other allows them to fill the gap in the production and design work.

Cooperation with other shipyards in the world such as Mil Davie in Quebec, Canada and Yang shipyard in China expands their market base and share in the profits.

The overall concept of modular construction has allowed commercial ships to be built at lower cost to the yard, and shorter time frame for the owners. The concept also allows the yard flexibility with subcontracting. A number of suppliers provide excellent quality and less expensive units than can be built within the yard. As an example the yard subcontracts from Poland the House-superstructure. This very large unit is fully outfitted, beds, sheets, to soap in the showers as a turn key unit and is supplied to the yard by barge after the engine room is outfitted.

The shipyard has developed a modular design that meets and exceeds the classification society standards, but most importantly customer requirements thus ensuring an exceptional product for their commercial customers. Finally they have gone one further step through the development of a flexible private ship financing in order to meet shipowner freight rate requirements and profits. Lastly and most important the shipyard is meeting Germanys marine and shipbuilding needs which allow an maritime industrial nation to keep its independence.

Figure 14. 2500 TEU Container Ship with Concept of Platform Modules.



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New Orleans Hilton Hotel, New Orleans, Louisiana

Implementation Of Integrated CAD/CAM Systems In Small And Medium Sized Shipyards: A Case Study

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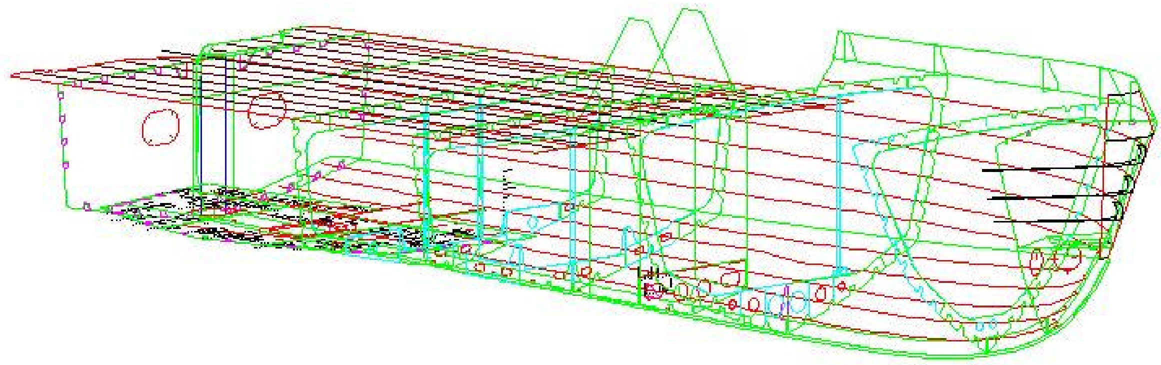

ABSTRACT

The Coast Guard Yard in Curtis Bay, MD implemented a PC/AutoCAD based CAD/CAM system and used it to construct a series of 15 M (49 foot) buoy tenders.

Implementing CAD/CAM is primarily a management, rather than technical, challenge. Performance-Based Management Techniques were used to develop the new system as an integrated whole, controlled and documented under ISO 9001. The process was cost-effective, required minimum retraining, was fully implemented in a few months, and was appropriate to a small shipyard building boats, but extensible as required to medium sized ships.

The authors discuss:

1) The use of Performance-Based Management and team-building techniques to help implement the process;

2) The use of process management techniques to document, control and systematically improve the process in order to remain competitive;

3) The process developed, including methods to allow varying levels of operator skill, geometry, weight and interference control, and development of automation techniques;

4) The lessons learned, the results in productivity improvement, and the future path for continuous improvement.

INTRODUCTION

When the authors first started this project and this paper, it was expected that it would involve primarily technical challenges. What we found is that the technical issues were relatively simple and that human issues dominated both the potential problems and the opportunities. This paper is about processes to implement change in general and their results as much as it is about the particulars of CAD/CAM.

Re-engineering For Integrated CAD/CAM

Computer-Aided Design/Computer Aided Manufacturing (CAD/CAM) represents a sea change in the role of the naval architect and in fact the entire process of shipbuilding. It blurs the traditional lines between design and production. For example, Computer Aided Lofting/Numerically Controlled Cutting (CAL/NCC) means that the designer is actually fitting steel at the

keyboard.

Though shipyards throughout the world have introduced various aspects of CAD/CAM piecemeal as substitutes for manual processes, the greatest improvement in shipbuilding is achieved by improving the interface between design, production, planning, weight control, procurement and logistics support and creating a new integrated environment where the same "keystrokes" that create the preliminary design are used through the entire shipbuilding process. Two important points are keys to increased productivity throughout the shipbuilding process:

First, technology advances should promote cross-functional process improvement rather than just automating existing tasks. The typical approach to implementing technology in many manufacturing organizations consists of little more than simply automating existing task structures. Assessing the impact of technology as an integrated system is the basis of process re-engineering and large scale improvement.

Second, Computer Aided Design is a new paradigm in ship design and construction. The authors intentionally use CAD as an acronym for Computer Aided Design rather than Computer Aided Drafting. CAD includes Computer Aided Engineering, because Engineering is a component of Design.

Viewing the paper drawings as an end product rather than an interim product is perhaps the single most limiting paradigm that has hindered productivity gains from CAD. The goal of the designer should be to produce information promoting optimally efficient production. Ship's drawings are an interim product as well as an end product. They must be optimized for production added value and possible adaptation or replacement just like everything else in the shipbuilding process.

Implementing this new paradigm requires an organized approach using a *systemic* management approach (a holistic view of all the Shipyard’s processes as one system), and process re-engineering as a tool within the context of the systemic approach.

The 49 BUSL Project

BUSL stands for Boat, Utility, Stern Loading. A BUSL is a small buoy tender equipped with an aft A-Frame. It backs up to a navigation aid, connects it to the A-Frame, hoists the aid, and rotates the A-Frame, placing the aid on the aft deck for servicing or replacement. The 49 BUSL replaces a Fifties vintage, 14M (46 foot) long boat. The new 15 M (49 foot) boat offers improved habitability so that the crew can overnight away from their homeport, twin engines for improved reliability and a hydraulic system independent of the main propulsion engines for improved control.

The 49 BUSL has a steel, single chine developable hull with a raised foredeck over a galley/mess/buoy workshop. A berthing space for four is forward of the habitability space. The deckhouse is on the foredeck and is aluminum with an explosively bonded joint to the hull. The deckhouse has a forward helm station and an aft facing station fitted with a second steering station and controls for the hoist, cross deck winches and A-Frame rotation. The aft deck is lower and fitted with flush tie-down fittings. The engine room is entirely under the aft deck, with a fuel tank separating the habitability space from the machinery space. Main engines are twin 220 KW (350 HP) diesels, and a combined generator/hydraulic power plant provides 20 KW of electrical power and 21 KW (28 HP) of hydraulic power. The lazarette contains the electronically controlled main hydraulic manifold, an air compressor for powering tools, the sewage tank and stowage for deck equipment.

The first two prototype 49 BUSLs were built in Bellingham Washington, but numerous changes were developed during initial operational testing, so that the production boats differ significantly from the prototypes.

This project was the first new construction at the Coast Guard Yard for some years and the relatively small size of the 49 BUSL offered an opportunity to introduce new processes with minimum cost and risk.

PART 1: ENGINEERING THE PROCESS

The authors have had the opportunity to witness process improvement efforts through new technology deployment at a number of shipyards and manufacturing organizations. When new technology fails to reap any real productivity improvements the reason is almost always the same: many shipyards try to implement new technology by simply automating existing processes.

This usually results in workers making the mistakes they have always made, producing the same rework they have always produced, and failing to meet the same requirements they have always failed to meet, except with new technology they simply do this faster. Even in the best cases, automating existing processes only produces savings in the specific process automated. Often any improvements resulting from automation are more than offset by the cost, labor and training needed to implement the new technology. Additionally, a common result is the production of products and services lacking in the features, functions and outcomes desired by those downstream in the process. This is especially tragic when this scenario occurs in the detail design phase of the ship building process - the real cost savings to be derived from integrating CAD/CAM is in the process design: the design group giving the production shops exactly what they need in the format they need, when they need it. Note that quite often the emphasis, even from the end customer buying the product, is on efficient product design. This emphasis is misplaced, because the key to success in manufacturing efficiency is in marrying the product design (the actual design features of the boat) with *process* design (how the boat is built.)

CAD/CAM and the ISO-9001 Quality System

Process design is the key to producibility improvements. Because of this, the ISO-9001 Quality Standard, which emphasizes process control, was a big boost to achieving success on the 49 BUSL project. The United States Coast Guard Yard is the first public shipyard, and the first public industrial facility, to obtain ISO-9001 certification. In retrospect, it would have been much more difficult to efficiently implement integrated CAD/CAM at a medium sized public shipyard without the discipline that ISO-9001 invokes. In the context of the CG Yard’s ISO-9001 system a key element of the planning literally involved detailing out each step of the process (and for critical steps, right down to the keystroke) and building consensus among the functional elements, such as the design functions and the production shops. Since the true advantage of CAD/CAM involves blurring the lines of distinction between design, lofting

and production, solid technical communication is essential to assure the requirements and potential efficiencies of each work unit are fully addressed. ISO provided that communication vehicle.

The real savings to be gained from integrated CAD/CAM technology comes from the impact of the technology on the entire process. ISO requires a level of process documentation and control that helps create a process focus. Therefore, as this technology continues to advance the value and potential benefit of an ISO style process management system will increase. ISO provides the framework that is needed to successfully focus on the cross-functional impact of the CAD/CAM technology. Much of the benefits of integrated CAD/CAM lies in the production of templates, fiduciary markings which eliminate measuring on the shop floor, improved fabrication shortcuts and by reducing the number of times a boat is redrawn by the various interim users of the geometry. All of this requires carefully coordinating the detail design with production because shipfitting is done electronically on the computer's "lofting floor" instead of on the production floor.

The key to launching any successful comprehensive process change is thorough up front planning. The CG Yard's ISO Quality System provided the foundation and requirement to develop and successfully deploy the detailed process steps. In order to implement the Integrated CAD/CAM process at the CG Yard, several quality technology tools were used. Initially, a scaled-down version of the Quality Function Deployment (QFD) planning method was used. In summary, the QFD approach provided the context to define the required features, functions and outcomes of each CAD/CAM product, such as fully lofted, true geometry detail design drawings, and interim products, such as roll sets and construction templates and fiduciaries.

One note of warning regarding ISO: shipyards that seek to obtain ISO certification as an end in itself are most likely missing the full benefit. The real benefits of ISO are only achieved when ISO is coupled with a policy of continuous improvement. ISO degenerates to little more than a paper chase for organizations that do not pursue continuous process improvement coupled with ISO as a means to institutionalize continuous improvement, rather than an end in itself. ISO probably is a waste of money for organizations who do not have a policy of continuous improvement. The real benefit of ISO is that it provides the beginning point of real process management that involves both process control and process improvement. Documenting processes is an expensive and time-consuming undertaking and little worth the effort if nothing will be done with this mountain of paper resulting from process documentation.

ISO Provided A Starting Point To Help Eliminate Suboptimization

The Coast Guard Yard, like most all traditionally structured shipyards, has a job shop structure. The organization is broken into shops organized along disciplines, such as inside machine shop, outside machine shop, welding shop, engineering hull branch, engineering machinery branch, etc. A weakness of this type of organizational structure is that it tends to create a myopsy among functional managers wherein self concern and turf protection become more important than efficiently accomplishing the work from an overall project perspective. ISO can help serve as the initial beachhead to address this suboptimizing mindset, since it requires as a minimum that cross-functional processes, called Management Operating Procedures (MOPs) and Discipline Specific Operating Procedures (DSOPs) be documented. The mere act of documenting important processes brings a great deal of understanding and brings into the open some obvious inefficiencies that were not so obvious before the processes were documented.

Most important, ISO provided a springboard to create a process improvement system. Once the minimal requirements of ISO were met, the CG Yard established a process improvement system which consisted of the following basic elements:

Identify Processes for Improvement:

Initially picking top priority processes for improvement seemed like a trivial task to some managers, because each thought it was obvious which processes needed improvement. But this turned out to be an area of significant disagreement among managers. What actually needed fixing or improving depended one's perspective. Therefore, the CG Yard used a consensus-building process to determine process improvement priorities. A consensus-building approach was used to determine priorities since everyone's commitment and support was needed for the cross functional boat building improvement efforts. Several criteria were used to prioritize processes:

- *Improvement Opportunity*: How "broken" was the process; how much of an opportunity was there to improve the process?
- *Business Impact*: How much impact is there on the business? This factor includes things like how central the process is to the core of the Shipyard's business, how many people are involved in the process and what would happen if this process was performed poorly?
- *Customer Impact*: To what extent did this process impact customers and what would happen in terms of customer impact if this process were performed poorly?
- *Changeability*: How much power does the shipyard have to change the process? For example, processes such as procurement are regulated by the Code of Federal Regulations and difficult to change, so improvement of these processes had low priority.

The above criteria were used to build consensus in order to get the integrated CAD/CAM process improvement initiative into the Shipyard's business plan. This is because some managers saw an integrated CAD/CAM process as a threat, since the efficiencies to be gained through reduced labor-hours would be made in their functional areas. As an aside, this example provides testimony of the need for every shipyard to have a business plan that is backed by senior management.

Managers At The CG Yard Are Process Owners

The CG Yard defines Process Ownership as the assignment of responsibility for how well a process operates, not only within functional areas of responsibility, but how well the process

operates in each of the functional areas through which the process passes. Process ownership by a single manager was a key to the success of the 49 BUSL construction project. Ownership of the CAD/CAM process involves not only changing large portions of the way design drawings are produced, but includes integration of the design itself with the fabrication process. The person at the CG Yard with responsibility for making this happen was the CAD/CAM Process Owner. Ownership of the interface between the detail design, numerical lofting and erection process was assigned to the Chief of the Naval Architecture at the shipyard. The CAD/CAM Process Owner had responsibility for how well the needs and requirements of the production shops were met. This required the process owner to gain intimate knowledge of the erection process and then ensure that the full benefits of numerical lofting were brought to bare. Additionally, under the ISO system, the process owner has responsibility for monitoring his/her assigned process to assure it continues to operate in accordance with ISO documentation and without interference from competing functional interests.

According to W. Edwards Deming, one of the Seven Deadly Diseases is organizational churn: the rotating of senior management every few years. This results in senior managers never truly understanding the profound aspects of the organization's processes and the organization's business they lead. Further, a "constancy of purpose" is never established, which is the first point of Deming's fourteen points of good management. As a public shipyard the Coast Guard Yard suffers from this malady since senior management, which are almost all military personnel, rotate every two to four years. Therefore, the benefits of ISO are particularly significant at the CG Yard since ISO requires that a third party verify that in fact each of the functional areas of the shipyard are at least meeting a minimum quality standard with respect to process and document control. Unfortunately, as in many government organizations, some middle managers have learned the dubious skill of being "quality pretenders:" that is, they appear to be committed to the quality efforts without ever really gaining an understanding of systemic management beyond the buzzword level. In fairness, this probably is attributed to the fact that middle managers often perceive they have the most to lose (in terms of power) in crossfunctional improvement efforts. Therefore, a benefit of ISO is that it requires management at all levels to adhere to a minimum level of quality compliance. When all elements of the organization are meeting at least this minimum level it allows those parts of the organization, and those managers who are really committed to the improvement efforts, to move the entire organization ahead.

CAD/CAM and the Malcolm Baldrige Quality Award Criteria

To make the concept of Continuous Improvement (CI) a tangible, institutionalized reality, the Coast Guard Yard is using the Malcolm Baldrige National Quality Award (MBNQA) Criteria. This criteria provides the framework for a performance-based management system, meaning the Baldrige is a management system that is based on measurement, with *all* elements connected to the strategic objectives of the organization through a system of credit and accountability. The Baldrige criteria heavily emphasizes using systemic, systematic approaches to achieve success in key indicators of tactical and strategic results. The CG Yard completed a self-assessment against the criteria in 1993. Even though the CG Yard was in its tenth year of applying quality principles, the self assessment score was less than 160 points out of a possible 1,000. After aggressively pursuing implementation of a performance based management system, the CG Yard was evaluated by third party examiners to be at a score of over 700 points (note that winners of this award score in the 800 point range.). This paper is not about Baldrige Award aspirations but how the MBNQA helped implement fundamental changes to core processes that involved CAD/CAM.

The CG Yard built a management system which linked each of the three levels of measurement using the Baldrige Criteria as the framework: the Organizational Level of measurement, the Process Level of measurement and the Job Performance Level of measurement (i.e., the individual Managers performance appraisals.) Specific numerical goals were then established for each measure and each level of measures and strategies were developed and deployed to achieve these goals. Therefore, managers had motivation through a measurement system to cooperate with crossfunctional improvement initiatives, even if they perceived these efforts to not be in their own personal interests. This approach provided credit and accountability for making improvements, such as cycle time reduction, product/service quality improvement and cost performance improvement. Initially, it may seem unnecessary for such a system to be deployed, since it can be rightly assumed that all managers want to see the shipyard succeed. However, because of the job shop organizational structure, the responsibility for success and improvement of cross functional processes had to assigned to individual managers- and this success had to be measured and aligned with the strategic direction of the organization. Managers find it very difficult to break the suboptimizing mindset unless they are given additional incentive to do so. For example, key managers within the CG Yard saw the implementation of an integrated CAD/CAM system as a threat, since the new process meant that many less labor hours, within their divisions or shops, would be needed. To prevent this, Quality Management Boards, comprised of all senior managers, made these important decisions through the business planning consensus process. Additionally, using the Baldrige Criteria as a roadmap, a system was established in which core processes were systematically selected for improvement, managers were assigned ownership and held accountable for improvements which were determined through measurement. Without this institutionalized approach to continuous improvement it is doubtful that a public shipyard would ever be able to make the improvements needed to stay competitive.

The Key to CAD/CAM Success:

> *"Engineers and Designers Need to Gain Profound Knowledge of the Erection Process and Incorporate Product Design and Process Design Producibility Features into the Detail Design."*

One of the most important responsibilities of the CAD/CAM process owner is to gain profound knowledge of the erection process in order to assure that detail design drawings fully incorporate the product AND process features which are now made available by the highly accurate electronic information. Traditionally, the mindset is that production has the responsibility to ask for what they need. Even a concurrent engineering (CE) approach does not address fully the CAD/CAM producibility issues, since CE focuses primarily on product design. However, production has no way of knowing the process design impact of numerical lofting capabilities and what design can provide to make the fabrication and erection more efficient. Rather, it is incumbent upon design (or those upstream in the process flow) to determine the needs and requirements of those downstream in the process. This is easier said than done, especially when the production floor may not be able to articulate the desired design features and functions in a way that is meaningful for the design effort. The process owner must lead the effort in:

- obtaining a clear understanding of every aspect of the fabrication process;
- drawing out from production personnel exactly what those design aspects that will promote efficient fabrication.

No Process Is An Island

The first corollary of Deming's Theory of Profound Knowledge is that if management is going to improve its organization it must gain profound knowledge of the processes and systems which comprise the organization. Processes like CAD/CAM require even more comprehensive understanding than most processes, since this process more than any other has the ability to affect almost every core ship and boat building process in a shipyard, yet at the same time involves a degree of technology that can be fairly challenging to explain to upper management and non-technical personnel.

THE CONTINUOUS PROCESS IMPROVEMENT MODEL

Figure 1 illustrates the basic approach used for implementing process improvement. The first phase basically involves documenting the process and getting rid of the "obvious" waste. The second phase involves establishing basic guidance and making decisions about what needs to be improved. Issues such as what needs to be done, who needs to do it and upper management authorization and support for the changes are established at this phase. Phase III involves actually implementing the changes, working out the details of making the process changes work and then measuring the results to determine if the implemented changes actually improved the process. Once Phase III is accomplished, the stage is set to actually re-engineer the process.

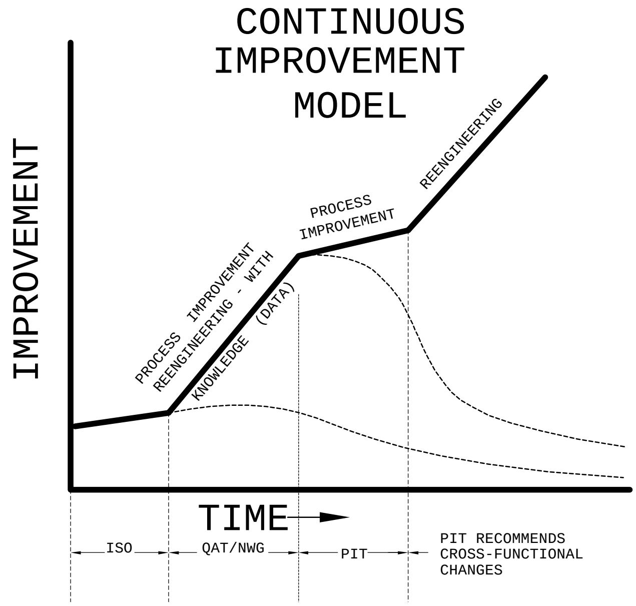

Figure 1

Organizations fail at process reengineering by going directly from ground zero to the process re-engineering phase without taking time to develop profound knowledge of what they are trying to improve. This knowledge comes from first documenting the process and second (and most important) trying to improve the process. According to Dr. Deming, nothing provides as much knowledge about a process as trying to improve it. This is the theory of continuous improvement: the very act of trying to improve a process will precipitate the development of profound knowledge about the process so that the significant risks that accompany process re-engineering (which involves massive process change) are mitigated. However, when organizations try to re-engineer processes that are barely even documented, disastrous consequences usually result and the reengineering effort degenerates to little more that a very poorly planned reorganization.

The thin lines in Figure 1 indicates that at each phase of the improvement cycle, if the commitment to continuous improvement is lost, the process invariably reverts to its initial condition. This subtle aspect of continuous improvement is emphasized by the fact that shipyards that do not maintain a commitment to continuous improvement actually look like they are moving backwards when compared to shipyards that have institutionalized this principle.

PHASE I: The "ISO" or Process Documentation Phase

Phase I is the Process Identification and Documentation phase shown in Figure 1. The CAD/CAM process was institutionalized using the existing ISO Quality System, with basic process documentation, and process ownership assignment. The first step in this process was to document the process as it currently operated (without fully integrated CAD/CAM.) Some time was spent finding out how leading shipyards and marine engineering

design groups perform integrated CAD/CAM. The industry leaders in this process were identified by using competitive comparison measurements, such as labor hours per ton of lofted steel and the level of integration of the detail design and numerical lofting processes with other processes. Related processes included weight management and purchasing documents (bills of materials) development.

Assemble a Cross-functional Process Improvement Team

At the beginning of the implementation of integrated CAD/CAM, the CG Yard loft shop was separate from the Shipyard's engineering design division. In keeping with U. S. shipyard tradition, these work groups were barely on speaking terms. However, since participation, cooperation and commitment were needed from both the design and loft functions and the ship fitting shops, a cross-functional team was established which included players from each of these areas. Team building was emphasized during this time and some time was invested in team building training, such as concurrent engineering training.

Establish Project and Team Objectives and Goals up Front:

Successful process re-engineering requires identifying the key requirements of the overall process. Since the CG Yard is a public shipyard, objectives of the re-engineering process were to:

- Optimize internal and external customer satisfaction by systematic aligning with the customer's desires for ease of use, timeliness and certainty;
- Minimize costs while optimizing product quality;
- Provide a consistent, documented, repeatable level of quality, especially regarding timeliness;
- Accurately predict, monitor and compare (to industry leaders) key indicators of process success, such as cycle time, labor costs, product (including interim product) quality and schedule performance;
- Provide a steady workload and reliable, secure employment for the workforce with opportunities for team contributions;
- Ensure that all interim products add an appropriate level of value; where interim products are a contract requirement but fail to provide added value (frequently a result of obsolescence caused by the CAD/CAM technology) eliminate them via the Engineering Change Proposal (ECP) process;
- Automate CAD processes where appropriate using CAD macros and programs;
- Identify and prioritize opportunities for improvement by establishing a detailed plan for implementing changes.

<u>Build The Team Dynamic.</u>

Of all the factors that led to the success of the 49 BUSL Construction Project, building a healthy team dynamic was probably the most important. This is probably the most neglected aspect of implementing new technology. During the early stages of implementation, it quickly became evident that trust among team members was a fundamental ingredient that was missing in the initial CAD/CAM process team dynamic. The newly formed team was understandably concerned with job security, or jobs disappearing as a result of implementing a more efficient CAD/CAM process. A key to success was a commitment on the part of the process owner that no one would lose their job as a result of implementing CAD/CAM. Traditional loftsmen were given the assurance that they would be cross-trained to perform not only numerical loft functions, but engineering and design work as well.

<u>Establish Partnerships Between the Shops</u>

Trust and healthy interpersonal dynamics were established on the CAD/CAM team using a method gleaned from the construction industry: mutual goals were agreed upon and basic rules of interpersonal conduct were established. Although this was done informally for the CAD/CAM team, basic ground rules of behavior were established and enforced by the team, such as practicing the art of "good-mouthing" one another and other rules of interpersonal conduct. Most importantly, agreement was reached to handle problems that occurred *within* the team. These few simple ground rules had as much to do with the success this team experienced as any other single factor.

<u>Document the New Process With Expert Help.</u>

Once the cross-functional team was assembled and operating, expert guidance specific to the Shipyard's equipment, physical plant, in-house expertise and specific to the 49 BUSL Boat Construction Project, was obtained. Two full days were spent with a subject matter expert mapping out the CAD/CAM process in exacting detail. During this phase detailed work instructions were developed which documented the critical steps of the CAD/CAM process right down to the key stroke. Additionally, each designer and lofter received one-on-one training to ensure there were no misunderstandings regarding what was required. As little as possible was left to chance. If it was thought of, it was discussed and documented. An informal, scaled down version of the Quality Function Deployment (QFD) method was used to catalog interim products and product features. The net effect was that this approach enhanced understanding, provoked communication and provided the baseline upon which to make very specific improvements. Additionally, integrated, internal, focused CAD training was critical to obtaining improved productivity. CAD training from general sources such as community colleges has value in initial implementation, but success came from providing very specific, targeted training just as it was ready to be applied.

Phase II: Process Improvement

Phase I of the CG Yard's Continuous Process Improvement model involved simply documenting existing processes as they currently operated. This was done for the CAD/CAM process to establish a baseline. However, since integrated CAD/CAM was a new process, this phase involved simply identifying in fairly broad terms what had to be done to change from a traditional lofting process to a full blown integrated CAD/CAM process. The method for accomplishing this is called "Boxing the Process", but in short, it consisted of assigning responsibility to specific individuals for fleshing out the details of each step in the new process.

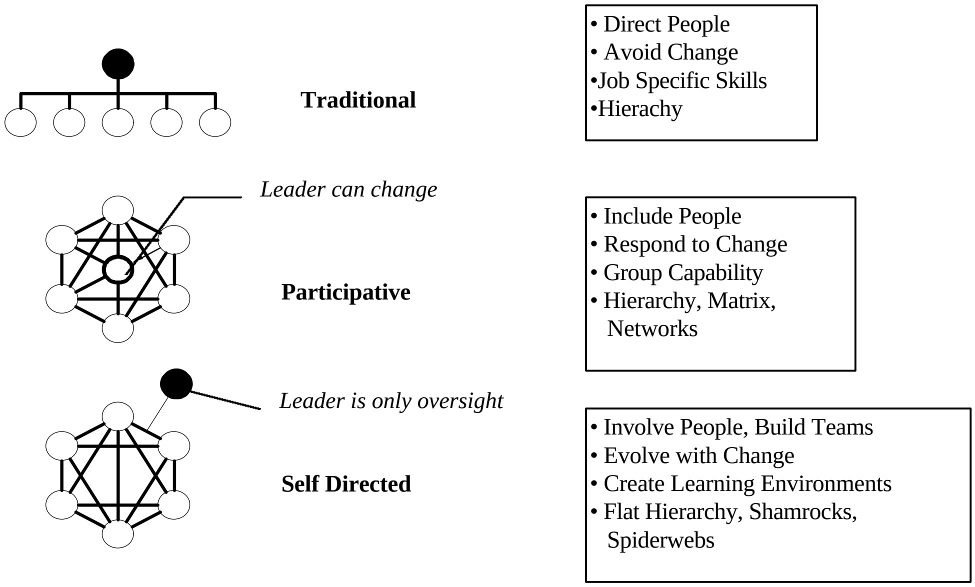

Figure 2

Phase III: Process Measurement

Since this was a new process, this phase essentially consisted of measuring the specific lofting costs and detail design development costs against shipyards and marine engineering companies that are established leaders in integrated CAD/CAM technology. Once the major players in CAD/CAM were identified, it became a matter of gaining understanding of what they do and how they do it, and how to adapt it to the Shipyard's culture and level of technical expertise.

- The measure that was used for initial estimating and competitive comparison was *Pounds of Lofted metal per Labor Hour*. Performance targets for this measure, based on comparisons with other NC lofters, ranged from fifty pounds of lofted steel per labor hour to over 150 pounds of lofted aluminum per labor hour. (This variance is partly due to plate thickness and other effects of vessel size, but is also indicative of opportunities to improve design productivity.) For estimating purposes, the number of plates (steel or aluminum) that will be required provides a relatively good rough estimate of required loft hours. However, more meaningful comparisons, which partly remove the effect of part and boat size, are provided by the following measures:
- *Labor hours per square foot of molded surface (or lofted area.)* This is an easy number to know after the lofting is complete, since CAD macros can automatically track this number. A competitive performance goal for this measure is about 20 square feet of unburned per labor hour.
- *Perimeter Feet per Labor Hour (Length of burn path per hour).* A competitive number for this measure is about 25 feet per labor hour.

Phase IV: Process Reengineering

The heart of successful process re-engineering is proper selection of the cross-functional team structure and team management. The type of team structure that was used to implement CAD/CAM was flexible and was changed to suit the rate of success and progress the team experienced while implementing the new process. Three of the five basic types of team structure were used:

- Traditional;
- Participative;
- Self Directed.

These basic team structures are shown in Figure 2. In brief, the traditional team approach involves minimum risk but also limited potential for creativity and breakthrough. Creative potential increases as team structure moves from traditional to participative, to self-directed; but so does the risk.

For the 49 BUSL, there was minimum tolerance for "emergent outcomes" (i.e., no room for failure.) It was widely believed within the Coast Guard that if the 49 BUSL project was unsuccessful in terms of cost, schedule and craft performance, most likely the CG Yard would be closed. Therefore, the initial 49 BUSL design team structure was a traditional structure. Process features that were absolutely crucial were not debated or consensed upon. The team was directed and held accountable for proper implementation. Traditional roles of team leader and team members were established; the team leader provided specific direction regarding software selection, training requirements, a basic outline of process steps, time constraints, individual responsibility and accountability for results and coordination and communication between the key functional elements. Once these constraints were met the team quickly moved to a participative structure, in which a limited amount of decision-making through consensus was permitted, with the team leader retaining authority to make overriding decisions. The team leader continued to coordinate the group's interactions but retained authority and accountability for decisions. Team members for the most part found this authoritarian structure acceptable as long as the

structure was defined up front and it was clear which decisions would be reached by consensus and which were subject to the team leader's final decision.

Synergy occurred when the team experienced initial producibility successes and an attitude of cooperation and coordination became firmly established. This level of team maturity allowed the team to move towards a self directed structure and became a truly energized team. With this structure the team was able to make decisions for itself and take appropriate risks to try new applications of CAD/CAM on different aspects of the project. The individuals began to further refine their own roles, identify problems and opportunities for themselves and were fully accountable for their decisions. The role of team leader became one of oversight. Actual team leadership became variable and informal in that different team members stepped forward at different times to lead the team based on specialized technical expertise and ability, personal leadership strengths, and individual temperaments and energy levels. During this period, major breakthroughs impacting efficiency in both process and product design occurred.

The most valuable product and process design improvements came from the workers themselves: the persons actually doing the CAD/CAM work originated the truly significant breakthroughs that achieved real savings and substantial improvements in product quality. The traditional management approach would never have produced these savings. The workforce achieved these results in spite of mistakes made by senior management on this project. It was the ISO Quality system, coupled with the team design strategy and a commitment to continuous improvement (by senior management) that provided the framework to mine the real gold of creativity and professional expertise that was hidden within the workforce.

During this phase of the project employee job satisfaction dramatically improved, enthusiasm became the norm, employee-originated ideas were suggested and implemented; team members reported how the work had become enjoyable (a rare experience in any shipyard!) These are the ingredients that make a truly productive workforce.

<u>Senior Leadership's Role</u>

The role of senior leadership in implementing the system was significant. Senior leadership established a performance-based management system (management by measurement) and shared in the responsibility for the risk associated with implementing fundamental changes to core processes. Senior leadership did this by giving whole hearted, public support for the changes and by providing the resources needed to ensure success.

IMPLEMENTING INTEGRATED CAD/CAM

The ultimate goal of the CAD/CAM process improvement is an integrated electronic *product model* containing all lofting, structure, outfit, weight and purchasing information in electronic format. It is helpful to note that a CAD file is not a picture; it is a database containing graphic and non-graphic elements spatially referenced to each other. Use of non-graphic, electronically inserted information (called Attributes in CAD software applications) can encode virtually any required information in the model. Traditionally, documentation of ships has been accomplished using paper drawings as the model of the ship for construction. However, this was not always the case. Back when ships were wooden (and men were iron) a three dimensional scale wooden model, or Admiralty Model, was the means of communication between the designers and the builders. The dimensions and other hull defining characteristics literally came right from this scale model. Computers have returned this concept of a three dimensional electronic Admiralty Model. Once again the primary means of communication between designers and builders is the three dimensional Admiralty Model.

Because the model is developed in electronic format, it can be used by all the functions of the shipyard from cutting parts to designing pipe to ordering materials, maintaining logistics records, and palletizing parts for inventory and workflow management of the assembly process. As an aside, this approach can be used for logistics support throughout the lifecycle of boats and cutters. However, development of the conventions and processes for such a model is a daunting task and will require organizations such as the Coast Guard to take a systemic management approach to boat and cutter lifecycle management.

For the shipyard, the areas with the highest, most rapid payoffs were selected for implementation first. This means the steel fabrication, since this area produced the largest immediate gains in productivity. Also, productivity gains in these areas helped create momentum which carried over to improvements in the outfitting, weight management and logistics database aspects of CAD/CAM as well.

During Phase I, the Process Documentation Phase, an outline of the basic eleven steps of CAD/CAM implementation were used to jump start development. This overview helped promote communication among the shops so that understanding and consensus could be built about how to approach and deploy an integrated CAD/CAM system. However, as employees were trained and the process progressed from Process Documentation to Process Re-engineering, the process steps rapidly became quite detailed, with work instructions documented down to the key stroke for some critical process steps.

<u>Develop the Process Overview</u>

The first step in developing the process overview is to identify key inputs and outputs. Frequently this varies between external customers so it is necessary to determine which inputs to the process, such as geometric constraints and drawing conventions, will be specified by the customer and which are left to the shipyard to determine. This is achieved by "boxing" the process as shown in Figure 3.

<u>Align With External Customers</u>

The richness of information available from CAD/CAM adds a new dimension to satisfying the final owner/operator of the boat, so aligning the process with customer expectations is a necessary step. Modern shipbuilding methods often require data in non-traditional formats. An example of this is data for plate cutting. This data is expressed exactly in the electronic files of the drawings themselves, which show the exact shape and dimensions

of all the parts. Additional dimensioning is therefore redundant and adds no value to the construction process. Yet drawing standards for Coast Guard boats require dimensioning which is of no value. An another example: end users usually need drawing data organized by system oriented classifications whereas the builder may needs geographic (Zone) or process (Process Work Breakdown) orientation of data. Therefore, this dynamic between the external requirements of the boat operator and the internal needs of the production shops must be addressed up front in the technical planning stage of the project. Development of the process overview, together with a Quality Function Deployment (QFD) approach allows all of the these needs to be systematically addressed.

This process of alignment with external customers was not implemented for the 49 BUSL project because the data needs of the boat owner, who was also a Coast Guard entity, were already well known and well defined. In retrospect, a formal alignment process would probably have benefited the process by giving the owner a better understanding of CG Yard processes. In turn, this would have allowed modification of the drawing and other data requirements to streamline design and still retain the value needed for the operators. As a result, the CG Yard produced drawings in conventional 2D format, organized by Ship's Work Breakdown System. This requirement had negative impact in that unnecessary drawings and drawing features were developed.

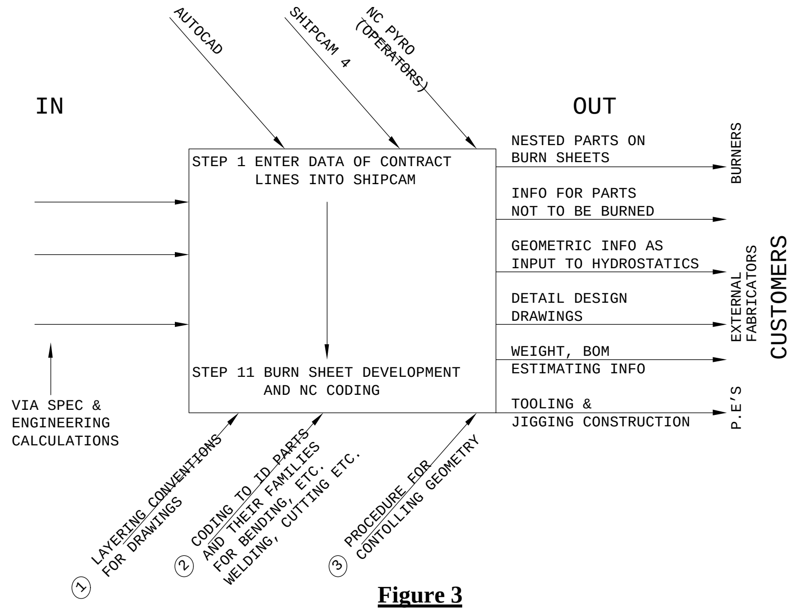

Figure 3

Align with Internal Customers

Internal customers and suppliers are essentially those workers within the process. A formal alignment process was used with the production shops and other functional work units to determine internal customer needs and interim product features and functions. This is a critical task because it has a dramatic impact on productivity and efficiency. In order to benefit from CAD/CAM technology, internal customers and suppliers must meet and develop technical and specific alignment throughout the steps of the design and construction process. Alignment here means establishing specific requirements for interim product format, features and functions. An example of a function is specific requirements responsiveness for design changes that were needed after the drawings were released to the shops for production. The CG Yard used an internal response standard of two hours for verbal concurrence from the Engineering department for proposed design changes, with documentation, including electronic and red line markups with a Drawing Change Notice to follow within two working days.

Figure 4 shows the workflow in "swimlane" format which emphasizes the relationships between internal suppliers and customers within the process. Depicting the workflow in this manner helps emphasize those areas of the process where cooperation and alignment are particularly important. These boundaries, "the white spaces on the organization chart," are where the greatest potential for inefficiency and problems occur and are the areas of greatest interest.

The introduction of an integrated approach to CAD/CAM must be handled carefully because it is intended to reduce the labor content in building ships. There will be resistance and even efforts to sabotage the new process design effort. However, if it is introduced as an opportunity to improve competitiveness and the workforce feels it has job security in light of the reduced labor hours that will be required by the new process there will be better cooperation. Additionally, the workforce must be given the opportunity to actively participate in the program. This was the approach that was used successfully at the CG Yard. In fact, many of the most advanced and creative suggestions were

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PROCESS:  INTEGRATED DETAIL DESIGN AND LOFTING
OWNER:    HULL BRANCH CHIEF

PURPOSE:  TO DEVELOP DETAIL DESIGN DRAWINGS THAT AUTOMATICALLY GENERATE
          THE ELECTRONIC DATA FOR THE NCC'ING OF SCANTLING PARTS
INPUTS:   CONTRACT HULL LINES, SCANTLING GUIDANCE & REQUIREMENTS, GEOMETRIC
          CONSTRAINTS, CUSTOMER'S SPEC, STRUCTURAL CALCULATIONS
OUTPUTS:  "BURN DISKS" (NESTED PARTS IN ELECTRONIC FORMAT) READY FOR NCC
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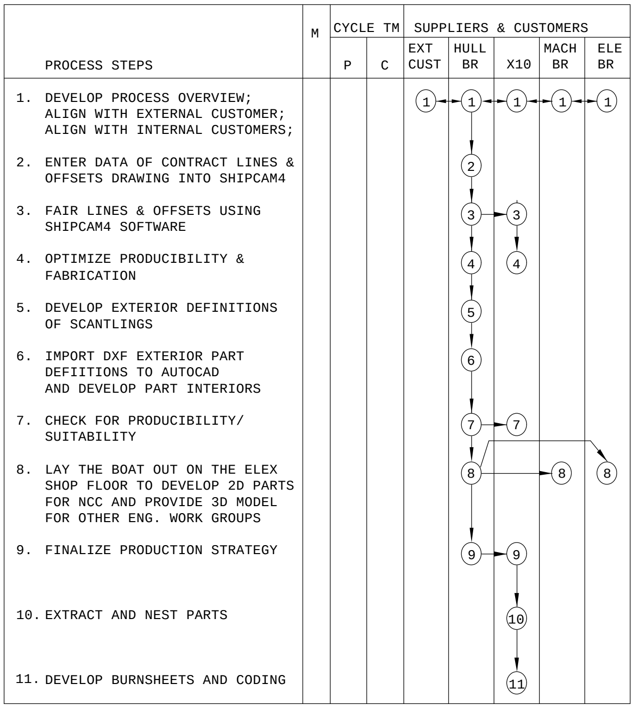

Figure 4

proposed by the workforce, once they were convinced that they were considered a key customer of the CAD/CAM process.

Next, a strawman process flowchart was develop as a starting point. This allowed those assigned to the task of implementing CAD/CAM to focus on the important implementation issues and reduced initial "storming," and confusion.

The design elements are suppliers to the production shop customers. Design personnel must determine the specific needs of the production shops in order to ensure that design is not accidentally suboptimizing the overall process. This requires a formal approach to eliminate overlaps, oversights and non-value added product.

1) The important interim products that design provides to production were identified. For the NCC process the products include:

- Fiduciary Marks or "nick ons," include dimensions, location markings, error proofing markings, part names, numbers and locations, accuracy control markings, reference lines, etc.;
- Generic Torch Code;
- CAD files of the nested plate;
- CAD files of three dimensional parts;
- CAD files in DXF format and
- Text files of offsets.

2) Next, the desired product functions, as stated by the production shops, was obtained. This is called the "Voice of the Customer" (VOTC). The production shops were asked to complete the following statement: "a quality (interim product) is one that is _________." Typical responses were phrases like "easy to use", "timely", "defect free.". Interim product features were obtained in a similar manner. The production shops were asked to complete the phrase, "A quality (interim product) is one which has ________."

3) The VOTC attributes were then organized and sorted into three categories: Timeliness, Ease of Use and Certainty. Examples of VOTC attributes for fiduciary marks and coding are shown in Figure 5. Fiduciary marks are dimensionally accurate marks placed by automated machinery on the metal itself that depict either information for part alignment or the location of some other part. Coding is text information such as part numbers for the part itself or for fiduciary marks.

4) The VOTC attributes were then translated into precise, measurable Substitute Quality Characteristics (SQCs), product characteristics that were designed into the products and then managed. SQCs have a clear relationship to the VOTCs and can be measured against an objective performance attribute. SQCs are developed by asking "How long...?" How many...?" How Often...?" How Much...?" The example SQCs for fiduciary marks are on the top row of Figure 5.

5) The relationships between the VOTCs and the SQCs were then determined. In Figure 5, minus signs depict an inverse relationship (as the value of the SQC goes down the satisfaction of the customer goes down;) plus signs (+) indicate a direct relationship (as the SQC goes up satisfaction goes up). Zero (0) indicates no apparent relationship. These are specific hard measures relating the satisfaction of internal production workers of the CAD/CAM process.

6) The SQCs were then prioritized by adding the number of relationships, both plus and minus, for each SQC. This identifies and prioritizes product attributes. A target value for the SQCs was then selected. This was the basis for communication between the internal customers and suppliers in the CAD/CAM process. This process therefore quantifies and prioritizes the desires of the production shop internal to the CAD/CAM process.

7) Executing the above steps in effect develops the first matrix, shown in Figure 6, of the four Quality Function Deployment Matrices, Figure 7. The VOTC table provides valuable input to the first QFD matrix, which is used to further refine the needs and priorities of the internal customers. The QFD provides great value in zeroing in on what is truly important and

PRODUCT ATTRIBUTE GROUPS	VOICE OF THE CUSTOMER	SUBSTITUTE QUALITY CHARACTERISTICS: HOW MANY MANHOURS ARE SAVED SORTING THE PIECE PARTS?	HOW MANY TIMES DO SORTERS/ASSEMBLERS HAVE TO STOP AND ASK WHAT MARKS MEAN?	HOW MUCH TIME IS SAVED DURING ASSEMBLY	HOW OFTEN DO ERRORS OCCUR DURING ASSEMBLY?	HOW MANY MISTAKES (INCORRECT MARKINGS) ARE THERE?	HOW MANY MANHOURS DOES IT COST TO MANUFACTURE MARKS?	HOW LONG DOES IT TAKE TO READ THE MARKS?
TIMELINESS	SPEEDS UP SORTING, PALLETIZING OF PARTS W/ SIMILAR MANUFACTURING REQM'T	+	-	0	0	-	0	-
	DOESN'T TAKE LONG TO MAKE FIDUCIARY MARKS	0	0	0	0	-	-	0
EASE OF USE	EASY TO READ (READABLE, LEGIBLE)	+	-	+	-	-	0	-
	EASY TO UNDERSTAND	+	-	+	-	-	0	-
	MAKES ASSEMBLY EASIER	0	-	+	-	-	-	-
CERTAINTY	MAKES ASSEMBLY MORE ACCURATE	0	-	+	-	-		
	DOESN'T COST MUCH TO MAKE AND USE	0	0	0	0	0	-	-
	DOESN'T HAVE ERRORS	0	0	-	-	-	0	0
	CONSISTENT SYSTEM FOR READING MARKS	+	0	+	0	0	0	0
	PRIORITY	4	5	6	5	7	3	5
	TARGET VALUE							

Figure 5 1

should be addressed first.

Develop the Schedule Strategy

One of the biggest opportunities for inefficiency in the CAD/CAM process that was discovered was differing expectations for schedule and sequence between the external customers and the shipyard. The sequence and rate of construction will determine the order and schedule of part cutting and hence the requirements for the lofting schedule and for manpower. Developing a schedule detailed enough to address these issues was found to save many labor-hours in inefficiency during production.

Construction Strategy

CAD/CAM produces extremely accurate parts, eliminates floor fitting and makes elaborate cutting details cheap - "the second cut is free." This provided radical changes in construction processes and strategy. Again, this required specific, technical alignment. Both the Production and the Design functions must have "profound knowledge" of each other's processes, needs and capabilities to find the CAD/CAM opportunities for productivity improvements.

Poke-Yoka, the Japanese term for error-proof part assemblies, provides unique tabs, slots or other features to align parts prior to welding. Part accuracy and elimination of field fitting helped change the order of assembly, making construction cheaper and helped improve advanced outfitting. Tools for assembly were cut along with the parts. All of these opportunities helped to radically improve production. However, this was made possible only because the designers knew what questions to ask the Production Shops, in order to know what to offer.

Data Conventions

Parts cut with an integrated approach to CAD/CAM are assembled, not made, by the workforce. Improvements in the quality of assembly were a significant opportunity for both producibility improvements and in streamlining design. Fiduciary marks are the best example. Fiduciaries were applied automatically with a pneumatic punch and showed alignment marks, accuracy control marks. Since they eliminate hand measurement and layout, they reduced labor substantially and improved accuracy. Fiduciaries also were used within the design drawings in lieu of some conventional symbols thereby eliminating non-value-added drafting labor. Other alternative data conventions included assembly drawings and jig setup tables- these provided significant productivity improvements.

PART 2 - THE PROCESS

The integrated CAD/CAM process eventually used for the 49 BUSL project differed from that originally envisioned. This showed the importance of using the TQM approach. Had the initial process been simply imposed based on the wisdom of upper management or a consultant, the project would have suffered greatly, but because flexibility and a team organization and consensus approach were used, a realistic, efficient process was developed from the initial one envisioned. For example, management initial envisioned using full three dimensional solid modeling. However, the workforce developed hybrid "2-1/2 Dimensional drawings." These drawings were essentially 2-D, but through the maintenance of the User Coordinate System (UCS) discipline, 2-D drawings were properly oriented and located within the 3-D wire frame model. This helped eliminate expensive training and schedule impacts that would have been caused by the lengthy time it takes to become 3-D proficient.

Software

The Coast Guard has been using AutoCAD, now Release 12, as its official CAD standard since 1990. Lofting software and the process for lofting had to be compatible with AutoCAD and had to operate on the existing available workstations, principally DOS based 486 or Pentium PCs. Use of PC CAD applications in shipbuilding is somewhat controversial, because it does not lend itself well to production of an integrated product model in the fashion that integrated, dedicated packages do. However, the Coast Guard is moving towards such a representation, but has not yet implemented it, so this was not important for this project. In addition, the use of linked PC CAD drawings and databases has been successfully used in the petrochemical process industry and other facilities management activities to produce a product model that consists of many related files rather than a single model. In the long run, the authors believe that this approach will suffice for

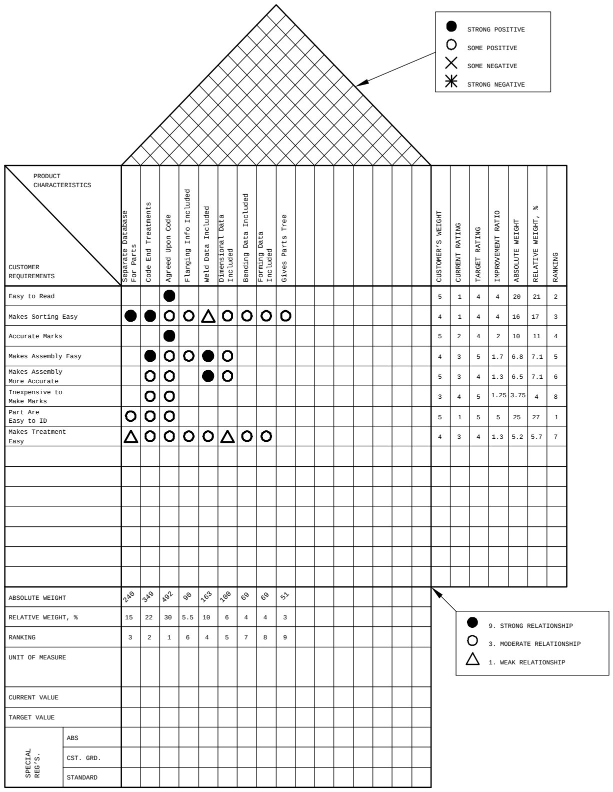

Figure 6

the Coast Guard and small ship and boat construction as well.

ShipCAM4 fairing and lofting software was chosen mainly because of it's orientation toward shipbuilding vice design, its cost, and its compatibility with AutoCAD and the existing workstations. The program offered numerous construction oriented features that were seen as necessary for long term use. ShipCAM has features that facilitated 2D drafting which turned out to be useful, though this was not initially appreciated. ShipCAM has a companion program for generating CNC code from drawings of the nested plates. This program added torch lead-ins, lead-outs and the tool paths automatically, so it produced labor savings in NC coding as well. One other advantage is that this software has only a single station license, so that there is no possibility of multiple models of the molded geometry being developed, which would cause the loss of geometry control.

Numerous AutoLisp routines were used which facilitated particular tasks, notably layer management and weight extraction. These routines were obtained from a combination of public domain sources, by programming in-house, or from a consultant firm specializing in numeric lofting. The consultant provided both their own routines and custom routines developed to the needs of the shipyard. The re-engineering process identified those areas of greatest value to automate and the cost of developing and purchasing was paid for many times over. Also, the numeric lofting was found to dramatically improve productivity of not only the lofting, but the designing as well. For example, the drawings that were provided by the customer to the shipyard had an unorthodox layering convention unsuitable for geometry control and NC lofting and cutting. CAD macros were used to properly layer the drawings to suit the CAD process. Another example included the problem that the initial contract guidance drawings that were provided to the shipyard were a mix of open and closed polylines. Macros were used to place the drawings in an editable format, then convert them to required polyline format for NCC.

2D - 3D

The generic method for computer lofting is to model the entire ship structure in 3D, then to subsequently extract the piece parts and flatten them to 2D, nest them and generate CNC code. Our initial plan was to follow this approach, with each designer working on specific major structural components, then assembling the entire boat from the components. There were several obstacles to this approach at the time the process was initially developed.

First, a simple 3D model would not provide the required documentation for the end user in the conventional format. AutoCAD provides a facility called "Paper Space" that allows a drawing to be built from 2D views on a 3D model and is a partial solution. However, the only way to control visibility of overlapping levels of a 3D model is to assign them to different layers. However, the CNC coding program has different layer naming conventions to distinguish between inside and outside cuts, marks, text, and extraneous (for the torch) information. This conflict can be resolved readily enough by a combination of layer naming conventions and software to rename layers during the transfer process, but with all the other demands, the schedule did not allow the time to develop and implement such a system. Using paper space also is initially confusing, and required more training than there was allowed by the schedule. Second, working in 3D in AutoCAD without any add-ons is somewhat cumbersome and requires additional training and experience. There are numerous add-ons ranging from major software to small utilities that improve 3D performance, but these also require training. Third, experienced designers are very comfortable in orthographic drafting. Finally, there are a substantial number of components that are not represented as required for manufacture in 3D, notably shell plate. Since these components have to be flattened to 2D eventually, the advantage of using a 3D model is diminished.

However, the value of a 3D structural model for visualization, accurate geometry generation, interference checking, and weight management are so significant that such a model had to be developed. Therefore, a combination of 2D and 3D processes were used as an expedient for this project. In retrospect, this may in fact be the most practical solution to the problem of the currently prohibitive costs associated with full blown 3D solid modeling. This approach also controlled the configuration as required by ISO and ensured that all designers were using the correct data.

The designer with the most 3D experience was ordained the "Geometry King." He maintained the ShipCAM database and gave other designers correctly oriented, properly UCS'ed 2D geometry of the molded surfaces derived from the ShipCAM model. The facilities for extracting 2D as opposed to flat 3D geometry provided by ShipCAM meshed well with this approach. Each designer then developed the piece parts flat in 2D and made conventional structural drawings. The designers then passed the flat parts back to the Geometry King who then placed them in the 3D model in their proper orientation for interference checking and

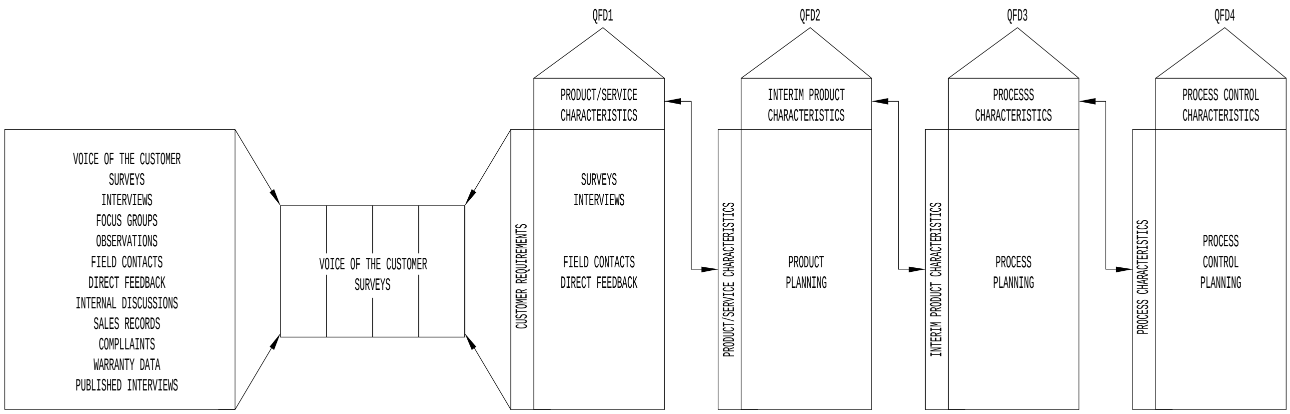

Figure 7

configuration control This process was actually very simple and effective.

The key to easy reinsertion of the parts and control of designed geometry was the procedure for preservation of the point of origin and axes throughout the design. When the Geometry King extracted the molded surfaces, he also extracted the current location of the boat origin in the 2D plane of the parts and the Z (out of plane) distance to the origin. He preserved this point on a dedicated layer and attributed it with the Z dimension plane, and the piece part or view applicability. The designers preserved this point and its location to the piece parts throughout the design process. Later, the Geometry King reinserted the finished part with the preserved origin at the model origin, rotated and elevated as required. This was a key procedure and was supported by specialized Lisp routines and origin blocks to eliminate errors.

small compared to the loss of productivity from

All-in-all, the use of this hybrid “2 1/2 D” procedure worked out very well. There were no bad parts and the design of the structure proceeded very smoothly. The time lost in the redrawing required by orthographic representation and part reinsertion was designers uncomfortable with 3D. Most important, this process has provided a bridge to 3D and Paper Space. The deckhouse was designed and detailed in full 3D and presented partially in Paper Space, and many of the designers had experimented with 3D or paper space in part most of the drawings by the time the structural design was complete.

Weight Management

The 49 BUSL is a low speed steel workboat, but because of a combination of maximum freeboard limits for the working deck and damage stability and draft limits, it is relatively weight critical. CAD/CAM provides extremely accurate weight data because “what you see is what you cut” and all cut parts are fully detailed. The 49 BUSL design effort allowed integrating CAD, the weight manager’s database and the Bills of Materials for purchasing. This greatly reduces both the time AND the mistakes that occur from multiple data entry.

Each part was attributed with a “partinfo” block by the designer, who input the type, thickness, and other aspects of the material. The designer then ran an AutoLisp routine that calculated the area properties and center of gravity of the part using data from the previously preserved attributed origin block. It then automatically inserted this data in the partinfo block as attributes. The weight manager subsequently extracted them from each drawing’s file to a database management program.

This process considerably streamlined development of Bills of Material and will be used for future generation of Integrated Logistic Support data.

PIPING AND OTHER OUTFIT

The 49 BUSL project did not use as extensive or tightly integrated a process for piping. There are several reasons for this. The CG Yard had no specialized software for piping analogous to ShipCAM; the piping would not be fabricated with numerically controlled machinery; the piping systems for such a small boat are very simple; the federal procurement regulations delay critical design information for most of the major systems. However, the main benefit to piping provided by CAD/CAM was still achieved. That is the ability to incorporate outfit oriented features in the initial structural cutting. A process to feed back penetration and integrated structure, foundation and bracketry data paid off handsomely. Additionally, interference checking became a realistic, systematic and highly accurate process.

The same system was used for providing backgrounds for piping, electrical and other outfit once the structure was firmed up. Each designer requested specific molded geometry or structure from the Geometry King and used it as background for his efforts. Since the structure geometry was absolutely accurate, this saves considerable effort, improves accuracy and eliminates structure/outfit interferences. Additionally, there is a cascading benefit which allows virtually all potential piping to piping, piping to electrical and ventilation potential interferences to be efficiently eliminated. When the systems were designed in 2D, the penetrations and similar structural interfaces were returned to the Geometry King, incorporated into the structure, and CNC cut.

The 2-1/2D approach to design development was also effective in eliminating interferences. In boat and ship design, interferences that are not caught until after the drawings are released for production and construction represent some of the most costly waste. When extensive rerouting and redesigning of piping and outfit arrangements is done on the shop floor, any benefits that could have been gained by CAD/CAM and careful erection sequence and scheduling planning are completely lost. When this occurs, scheduling pressures become the overriding concern, a free for all to obtain the easiest installation locations occurs among the shops and configuration control is lost. However, because the UCS discipline was maintained on this project, interferences were eliminated from the production drawings before they were released for production. An "Interference King" was given responsibility for preventing interferences. The Interference King used a 2 1/2 D composite drawing approach, which proved to be a cost effective method and much less expensive than trying to develop a full 3D model for interference checking. By way of background the shipyard had experienced poor results on past major renovation projects trying to use composites to prevent interferences. In retrospect, the reason that these early composite drawings failed to produce any real economic benefit were two-fold: (1) the background structure had to be used as reference to locate the new installations. This created huge, unmanageable drawings sizes when these various drawing were brought together in one composite; (2) the background structure was not accurate enough to be used as exact construction location references since the true (lofted) geometry was never incorporated into the detail design drawings before the new integrated CAD/CAM process was deployed. However, with true geometry drawings and the use of the User Coordinate System (UCS) discipline (in which the exact locations of everything is maintained) both of these problems were eliminated. For example, when checking for potential interferences with bulkhead piping penetrations generated by four or five different piping designers and a couple of electrical designers working in the same crowded areas, the following method was used: each designer was given a zone within which to work. Next, when the potential interferences were placed, the designers notified the interference king, who then blocked *only the penetrations* into the composite drawing. Instead of importing each entire drawing into a overall composite, just the several penetrations were "W blocked" and down loaded from their source drawings via the designer's CAD network. This approach was made possible because the exact x, y and z location of the penetrations were known and kept current with the (0, 0, 0) point of the vessel. The same approach was used to place and check for interferences of equipment and foundations. This approach allowed up to about 18 designers to work simultaneously with good coordination to meet production schedule demands.

PART 3: RESULTS

The results for structural erection were very good. Implementation of this integrated CAD/CAM process has resulted in structural construction cost ***underruns*** of over 25 per cent. Additionally, there were virtually no bad parts and erection, particularly on the second hull, when the shop had accepted that the parts would really, truly fit, went very rapidly. It is difficult to determine how much time was saved, because it had been some time since any new construction was done in the shipyard and there was no readily comparable data. However, and perhaps more important, the process, and therefore the CG Yard as a whole, was viewed by the prime customer as successful in this phase of the project as illustrated by the following quote from a memo written by RADM North, Chief of Acquisitions for the U. S. Coat Guard, the customer of the 49 BUSL project:

> *"I am especially impressed with the producibility improvements the CG Yard has implemented in order to build the buoy boats as efficiently as possible. The extensive use of computer resources for lofting and three dimensional modeling was particularly impressive and shows the CG Yard is effectively managing the leading edge of boat building technology."*

INNOVATIONS

The most surprising outcome was the spontaneous improvements generated by the workforce when the process became successful for steel. The team dynamic became an important factor, with many of designers and production personnel actually commenting that the work had become enjoyable. Because of this, the effort to find producibility improvements was championed by the designers and production persons. The following few examples illustrate that the most important factor impacting producibility is workforce moral, since the most important improvements were made by the designers themselves and not by management.

Structure and Joinerwork and Foundations

The designer responsible for joiner work independently developed a process to CNC cut all of the joiner panels, saving substantial labor hours. Also, features for rapid assembly based on Ready-To-Assemble (RTA) knockdown furniture concepts were incorporated. The designer then developed an integrated joiner foundation concept to support the panels and designed and numerically cut a jig to allow precision assembly of it.

Another designer championed the use of construction jigs for the habitability flat, the web frames, the transom and the bulkheads which resulted in substantial overall savings.

Piping And Machinery Composites

One of the piping designers independently proposed, developed and implemented the procedure for making composites of all the machinery, electrical equipment and piping based on the structural origin preservation procedure. This procedure was then extended so that it semi-automatically generated composites using the AutoCAD "external reference" (XREF) facility and the CAD network server. This procedure reduced interferences and improved arrangement planning, but more important, since it was developed spontaneously by the main users, it fit their needs much better than a system imposed

from above and was rapidly embraced. Thus, configuration is better controlled and interferences were virtually eliminated This system also increased enthusiasm for a move to 3D modeling. In fact, the last piping system developed used a quasi 3D process as a trial.

Deckhouse

By the time the deckhouse was developed, the designers were more comfortable in 3D, so they decided to develop it in full 3D using Paper Space techniques, including exploded assembly drawings. The sheet metal shop had been so impressed by the results they had seen in structural steel that they approached the designers to develop a full set of jigs to fabricate the deckhouse as well as the parts themselves. This approach not only improved production, and accuracy but helped to control distortion. The shop and the designers also set up predetermined standard details for the stiffeners, (which were rectangular hollow tube) in the deckhouse, acting as a self-directed team. As a result, the deckhouse is extremely fair and smooth, even though it is 1/8 aluminum. It was also built very quickly.

LESSONS LEARNED

The most important lesson from this project is that the critical issues in CAD/CAM are not technical but procedural and people issues. By empowering the designers and shop personnel to use the new technology to fit their needs, and by building a unified team, their energy and creativity was harnessed in a fashion that would not otherwise have occurred.

Fiduciaries

The use of fiduciary marking proved to be as big a savings as numerical cutting itself, provided that the shop's needs were met by the marking system. The initial alignment process invested significant effort to coordinate the requirements for marking, the most useful alignment marks and mark conventions and symbology. The result was that most of the measurement needed for assembly was eliminated which not only improved accuracy and reduced the chance for error, if saved considerable time on the shop floor. It is worth noting that the few assembly problems were all related to insufficient marking.

Templates

Initially, the shop was to develop all of their own templates, and design was only involved in part production. However, as alignment and the project itself progressed, the shop requested more and more templates such as the house and habitability flat jigs discussed above. Jigs were also produced for pre-fabbing the engine foundations. This proved to be another significant source of improved producibility. The low cost of producing relatively complex jigs improves accuracy substantially as well as speeding production.

Roll Sets

Roll sets are specialized templates used for guiding the roll and press operators in bending components. There were several parts that had to be re-formed. This occurred because traditionally the shop would have produced their own roll sets off of loft data at the same time they made the parts. Because they did not have the traditional information they were used to, they sometimes incorrectly rolled a part, or misused the template data they were given. Design found itself producing more roll templates as the project progressed, but often found that the information given the shop as to how to align the templates was deficient. This is an area that requires a great deal of effort to foster clear communication. Fortunately, very little time was lost in these incidents, but this is strongly attributable to the team building that occurred early on. There was no occurrence of the "blame game" that would be traditional, and each incident was resolved in a couple of hours.

ECNs

One of the most important improvements was in the flow of Engineering Change Notices from the shop to design. ISO requires that the drawings always match the boat, so that the shop could not fix errors on the floor without the concurrence of the designers and without documenting the change. However, the shop was traditionally reluctant to ask for ECNs because of delays. Design therefore made a commitment to get a reply to change requests or problems within two hours or less. As a result, the shop not only followed the ECN procedure fully, but used the drawings more carefully. Maintenance of this discipline saved over 4000 labor hours since it completely eliminated the need for as-built drawings, since the detail design drawings *were the as-built drawings by virtue of the ECN process*. However, even this substantial savings pales compared to the savings achieved in production itself through a disciplined approach to configuration control, which translates into interference control and prevention of suboptimized location of outfitting.

Developable Surfaces

Lines fairing is an emotionally loaded issue in a shipyard. The loft regards fairing as their sole domain and guards this prerogative jealously. As a result, the loft did the initial hull fairing and passed the first molded surfaces to the Geometry King in design.

The 49 BUSL is a developable hull form. An exactly developable surface has zero warp, and between two curves in space there is at most one such surface. However, there is often no surface with zero warp possible. As a practical matter, some warp is feasible in real materials, generally six to ten degrees. In this case there are many possible "plateable" surfaces. ShipCAM has controls on both allowable warp and on parallelity, the allowable angle between two adjacent rulings in the surface, sometimes called "fanning" because it produces fan-like patterns of rulings.

The initial bottom surface created by the loft had very little fanning but lots of warp. When the Geometry King trialled the plates by expanding them as a double curved mesh, they

showed some required stressing to fit. Since the stressed areas go red on the display and may require line heating, the plates were said to show "lots of heat". The loft and design met and decided that there was too much heat in the plates and that new surfaces had to be found, though the chines as faired by the loft would be kept.

When the allowed warp was decreased, the fanning had to increase. This produced an unfair surface where a butt or waterline crossed the hard line at the edge of a fan. This is common in lower speed boats where the chine and keel are not parallel. The solution was to extend the chines and keel arbitrarily aft until the unfair fan was completely off the real hull form. The bottom was subsequently trimmed to the true transom and was satisfactory. However, the team building effort again prevented potential conflicts.

Continuous Improvement

There are many needed improvements in this process. Piping, electrical and machinery must be addressed in the same fashion as structure, so software analogous to ShipCAM has been identified. The 3D skills of the CAD operators need to be upgraded and software aids for 3D are required. Production planning needs to evaluate the opportunities afforded by CAD/CAM to optimize their build strategy. However, the re-engineering process started with this project has successfully institutionalized continuous improvement, so much so that it is now happening spontaneously, and workers are now the drivers of change, rather than management. This is the promised result of empowerment and the most important point of this paper is that it actually works as advertised.

CONCLUSION

Integrated CAD/CAM

The integration of Computer Aided Design (CAD) CAD, Numerically Controlled Lofting, Numerically Controlled Cutting (NCC) and production afford substantial opportunities for improved quality, reduced costs, reduced calendar time and better data collection. However, the key is in fact integration, which in turn requires profound understanding of the entire boat design and construction process and all of the external and internal customer's and supplier's interim product features, functions and constraints. NCC can be a source of continuous improvement due to both the improvement of technology and the need to rethink and break down old paradigms.

Approaching CAD/CAM from an integrated process perspective offers is an opportunity to use NCC profitably, but requires careful attention to the principles of employee buy-in, quality management and leadership.

Change

U. S. shipyards must change to remain competitive. Public shipyards in particular have been accused, with some justification, of tenaciously resisting change. The Coast Guard Yard has implemented changes that radically affect many workers. There are many "broken rice bowls" in the shop and in the design office. Nonetheless, by applying TQM principles honestly, the CG Yard has embraced these changes and furthered them, improving quality and productivity. Other shipyards may not need or embrace our particular methods of approaching CAD/CAM, but they should embrace our methods of instituting change and continuous improvement. They work.

ACKNOWLEDGMENTS

The success of structural CAD/CAM in this project would have been impossible without the skills of the production workers, particularly their ability to weld with very little distortion. Joe Schoolden, the Composite King, deserves special mention for taking initiative and implementing the composite control procedure. Eric Jolley, of Elliott Bay Design Group, provided much of the special expertise and custom programming that made this project work. Additionally, Michelle Barry deserves credit for the numbered figures in this paper.

Lastly, the authors would like to acknowledge that the improvements that were made at the CG Yard would not have been possible without the vision and leadership of the late Captain Ron Gonski, US Coast Guard. His inspiration and his dedication to the development of the leaders around him will prepare the CG Yard for the challenges of the twenty first century.

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Simulation And Visualization Opportunities In The Ship Production And Maritime Environment

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ABSTRACT

This paper provides an introduction to the application of commercial off the shelf (COTS) and PC based simulation and visualization software in the ship production and maritime environment. It is intended to assist the shipyard manager, production engineer, naval architect and marine engineer in identifying simulation and visualization opportunities in the areas of production, project management, training, design, and port evaluation for vessel loading/unloading times. The desired features of simulation and visualization software for maritime applications are discussed, and a sample listing of both maritime and non-maritime simulation efforts is provided. In addition to this general discussion, two projects which utilize these technologies are described.

INTRODUCTION

Today, through the evolution of technology, simulation and visualization capabilities have been transferred from expensive main frames and work stations to affordable desk top computers. The software applications themselves have also evolved from specialized one-of-a-kind products to essentially commercial-off-the-shelf (COTS) products. This transformation has resulted in a much broader expanse of application for simulation and visualization technology. No longer are the tools solely used by large corporations, governments, and universities for complex, time consuming problems. Instead they are used by companies of all sizes for applications ranging from plant layout and training to analyzing and evaluating ship systems and sub-systems. The results that are being obtained through the application of these technologies include more informed operators, design optimization options, and, of course, the simple answer of whether or not a concept will work.

In order to provide some insight as to what is required to use these technologies, as well as to provide more detailed information on the benefits that may be obtained, two projects are discussed in detail in this paper. The first project entails the use of simulation software to model the mess line flow for a ship's galley while the second project involves the linking of visualization software with scheduling software. This latter capability allows for the 3-D visualization of ship production schedules, illustrating the effect on ship assembly and erection processes of modifications to that schedule. In addition to these two projects a number of other potential applications for simulation and visualization techniques in the shipbuilding and design arena are identified.

SIMULATION

Simulation can be described as a number of things, yet simply put it is both a process and a tool. It is a process when it is used as a method for modeling a sequence of events, and it is a tool when that model is then used to produce results which can be analyzed. This dichotomy in definition is also shown in the definition provided by *The New Lexicon Webster s Encyclopedic Dictionary Of The English Language* which states:

> *Simulation: a representation of a product, condition, or process in a different medium, e.g., computer, statistical chart, mock-up, esp. for the purpose of analysis.* [1]

In his paper "Introduction To Simulation", presented at the Winter Simulation Conference 1995, Andrew F. Seila, Professor, University of Georgia, concurs with this definition and further indicates that:

> *All simulations are developed to determine system performance under alternative designs or environments, with the objective of optimally designing or operating the system.* [2]

In other words, simulation allows one to experience and analyze a product, condition, or process as if it was actually occurring. This capability is extremely beneficial and has caused simulation to become a leading system analysis method.

Simulation is an excellent tool that can be used to analyze just about any level of system complexity. The complexity of the system is limited only by the person modeling the system, the physical capacity of the computer, and the software chosen for a particular analysis. The system must also be well understood by the modeler prior to being modeled. The analytical results obtained through simulation, and the visual representation of the model, provide an actual approximation of the system and can

carry credibility to the actual decision makers. In short, simulation brings a sense of reality to the analysis of a system. Simulation provides the capability of analyzing any stochastic system without regard to its structure or complexity.

Types Of Simulation Software

There are basically four categories of simulation software. These categories, and some example products, are identified below in Table I.

Classification Type	Examples
General Purpose Languages and Simulation Libraries	Fortran, Pascal, C, Algol, etc., and SIMLIB, SIMTOOLS
Simulation Programming Languages	GPSS, SIMSCRIPT
Interactive Simulation Programming Systems	SIGMA, CAPS/ECSL
Visual Interactive Modeling Systems	AutoMod, ProModel, Arena, Witness, SIMFACTORY

Table I. Simulation Software Classifications [2]

As can be seen by examining this table, simulation software products come in a wide variety of packages with a varying number of features and levels of difficulty. Each of these categories has its pros and cons. As an example, the 'Simulation Programming Languages' category provides users with a product that is a standardized simulation language from which to make his or her models. While this tends to provide the greatest amount of flexibility in creating models, whether they be small and simple ones or large and highly complex, this category also requires a lot of effort on the part of users. With products from this category the user not only needs to know the procedures that will define the model, but also needs to know how to:

- Program these procedures in the language of the selected product;
- Create the constructs which will allow information to be retrieved from the model as the simulation runs; and, if desired,
- How to construct graphical images to visually portray the model's processes in action.

Though not as flexible as the *Simulation Programming Languages* category, the *Visual Interactive Modeling Systems* category contains many of the same benefits with a shorter learning curve. At the low end of the spectrum in this category are the *user friendly*, *canned* products which combine a simple to use interface with pre-made modeling features. These products are excellent tools with which to model simple and small processes. At the other end of this category, vendor specific proprietary simulation languages have been added to the product providing them with the flexibility required to model large and highly complex processes. Even at this end of the category, users can still be constrained by the features of the inbred simulation language, as well as his or her own limits in understanding that language.

The exact method of simulation found throughout these categories of products, is still basically one of two types, either *time-independent models* or *stochastic processes*. Simulations involving stochastic processes represent the majority of the models analyzed with simulation procedures. They can also be further subdivided into either discreet event, or continuous simulation.

Discrete Event Simulation. Discrete event simulation is an incremental, or step by step, process where the simulation proceeds from one event to the next. The events can be either time or queue driven, and, either deterministic or stochastic in nature.

When the process is time derived it uses a fixed time step such as seconds, minutes, hours, days, etc., with which to advance the simulation. This method of modeling provides for a *real life* feel to the visualization of the simulated process. *Real life* in this case refers to the fact that the model is advancing as if it was a real time visualization or enactment of the process. In queue driven or variable time step simulation the time spans between events are not visually portrayed. The key word here is *visually portrayed*.

The variables used in discrete-event simulations models are also typically stochastic. This allows the incorporation of statistical probability analysis into the model providing for a much more accurate representation of the modeled events. The more accurate and detailed these stochastic processes are made the more precise the simulation results will be.

Continuous Simulation. Unlike discrete-event simulation, continuous simulation is not an incremental simulation process, but rather a 'start to stop' process that is primarily interested in showing the beginning and end results of the process being modeled. The actual approach taken in these models is to model the system as a differential equation where time is treated as a continuous variable. The solution is obtained by solving the differential equation. An example is using differential equations to construct a predator/prey simulation model.

Simulation Based Design

Although in existence for a number of years, Simulation Based Design (SBD), is a relatively new and up-coming technology that promises great returns. Part of this popularity is due to the rapid advancements in, and the increased availability of, desk top computers. It is a method, or process, that allows for a high degree of concurrent engineering between the design process, the simulation and analysis of the product, and the design decisions being made. In its current computerized format it has been applied to a great variety of problems; from evaluating manufacturing systems to analyzing public services and business processes.

Some areas of application for SBD in the ship design/production arena are shown in Table II.

By modeling and analyzing process flows in a proposed ship design or manufacturing process lane, problem areas, throughputs, and utilization factors can be identified. The simulation model can then be modified to remove the problem and/or enhance and optimize the overall design of the product or process being modeled. With simulation these changes and repeated analysis can be performed a number of times quickly at relatively low cost.

DESIGN	– Disembarkation Route Analysis
– Space Allocation Optimization	– Equipment Selection/Manning Analysis
– Space Arrangement Optimization	**PROJECT MANAGEMENT**
– Special Evolution Time Studies	– Schedule Development
– Equipment Selection Optimization	– Queuing Date Determination
– Galley & Mess Line Flow Studies	– Planning
– Equipment Selection & Manning Requirement Studies	– Acquisition Date Determination
– General Arrangement Studies	**TRAINING**
– Special Evolution General Arrangement Studies	**PRODUCTION**
– Identify Optimum/Correct Location For Abandon Ship Lifeboat Stations	– Shipyard Production Lanes
	– Shipyard Construction Planning & Work Load Leveling Aid
	PORT EVALUATION FOR CARGO OPERATIONS
– Evacuation Route Analysis	

Table II. SBD Applications In The Ship Design/ Production Arena

Simulation Software Recommendation. In modeling and analyzing processes involving the construction or design of a ship, or ship portions (e.g. galley area design and utilization), where the overall process to be modeled consists of a number of smaller processes, a product from the Visual Interactive Modeling Systems category of Table I that uses the Discrete-Event Simulation method is recommended. The reasons for this are:

- Ability to model by steps/events or queues;
- Availability of software;
- Ability to perform "what if" analysis during the simulation run; and
- Ability to subdivide a problem into distinct, manageable problem areas.

Discrete-event simulation software should have the capability of importing CAD drawings into the model as templates. This capability provides users with an added degree of flexibility for using CAD developed drawings as background templates over which a model can be constructed, or as background templates on which objects can be built. The former capability prevents users from having to recreate a drawing within the simulation product environment, while the latter option allows objects to be created and placed within the model being built that closely resemble their actual CAD drawings. These objects could represent stationary background objects or a specific type of vehicle within the model.

There are currently a number of software simulation products available on the commercial market that fall under the Visual Interactive Modeling Systems category identified in Table I. All of these products are 'canned' simulation packages in that they provide pre-constructed elements with which to construct the process model. The simulation models are themselves created by simply selecting the desired element, placing it at the appropriate modeling environment location, identifying the characteristics associated with it, and then linking it to the other elements of the model to show the process dependencies. The amount of programming actually required is dependent on the level of complexity desired in the model.

In selecting a product one should also consider the following factors in addition to the basic features of the product and those factors mentioned above:

- A user interface that provides the best format for ease of adding detail to a model after its initial construction;
- A user interface simulation language that is easy to understand;
- Software capability to develop and use sub-routines in the simulation code;
- Software that provides excellent graphical features, including true 3-D graphics, and the ability to create movies of the process being simulated for viewing on video cassette recording machines;
- Software that provides the ability to construct the model to scale in either U.S. customary or metric units;
- The availability of the software for both PCs and UNIX workstations; and
- The ability to model material flow processes, apply routing logic to the model, assign attributes to model elements, and apply statistical distributions to the processes being modeled.

Some examples of past process flow simulation applications are identified in Table III. These examples were taken from a wide variety of sources that include product information brochures and publications by the American Society of Naval Engineers.

PROCESS FLOW SIMULATION

Due to the ever increasing complexity of the ship design process, where the overall goal is to meet the owner's requirements while designing for affordability, the need for a tool that has the capability of analyzing and determining the characteristics of discrete event shipboard activities has emerged. In an effort to demonstrate the utility of process flow simulation software in fulfilling this need, a small pilot program was initiated that modeled the processes associated with personnel flow through a ship's mess line.

The mess line flow effort was approached in two phases. The first phase included the identification of the mess line process flow interactions that were to be studied, and the collection and development of data to represent these processes. The second phase involved the actual development and analysis of the process flow simulation model.

Process Flow Simulation Applications
Simulation and analysis of the LPD 17 starboard mess line flow
Evaluation of proposed Singapore Port changes/expansions
Use of simulation to create a tool for standardizing the layout of future Taco Bell restaurants
Use of simulation to improve the traffic flow through current Taco Bell restaurants
Simulation of the production processes of the Boeing 777
Simulation of the roll out celebration for the Boeing 777
Simulation of a steel stockyard operation in connection with a lay-out development
Simulation of a cutting shop in connection with the modernization program
Simulation of the entire prefabrication facilities at a Norwegian shipyard
Simulation of different ship construction approaches at a German shipyard
Simulation of different steel fabrication lines for various customers
Motorola and its partners simulated the entire supply chain for the manufacturing and delivery of the low earth orbit satellite communication system
Simulation of the John Hopkins hospital's main cafeteria serving process to both staff and visitors
Simulation of the LHA 1 Class cargo handling system

Table III. Process Flow Simulation Applications

The results that would be obtained from this model would provide the following information:

- The amount of time needed to feed the total crew and troop complement;
- The flow rate of personnel passing through the serving line;
- The number of personnel passing through the serving line in the first 21 minutes (21 minutes represents the allotted eating duration);
- The utilization factors of the Food Service Attendants (FSAs) and Mess Specialists (MSs) along the serving line, and of the FSA restocking utensils; and
- The effects of different mess deck seating variations on the time needed to serve the crew and troops.

As part of the investigation undertaken in Phase I, commercial kitchen standards were utilized, as well as input from Navy supply representatives. This information was used to select a menu to model, as well as to help identify the serving sizes, equipment capacities, process times, and personnel interactions associated with the utilization of the mess line. Another Phase I decision item was the extent to which the galley mess line area would be modeled. Because the task was a small pilot program, it was decided that an application of limited scope would be enough to demonstrate the utility of using a process flow simulation tool in helping to design and analyze food service operations. As a result, the actual scope of the process flow simulation model was reduced to modeling only the starboard serving line, half the ship's personnel, and half the seating capacity. In addition to the ship's personnel utilizing the serving line, the mess line support personnel were also modeled since they have a direct effect on the proper operation of the serving line. Other features that have been incorporated into the model include:

- The traffic flow of the crew and troops during meal time;
- The menu being served and the menu selection distribution of the crew and troops;
- The actions of the crew members in the serving line and of the personnel supporting the serving line, but not those in the galley; and
- The movement of the crew and troops to either of the two entrances into the Mess Deck.

The following sub-section provides a detailed description of the assumptions and methods used in creating the simulation model. The results that were obtained from this model are discussed in the sub-section titled **Simulation Run Results**.

Assumptions and Constraints

In addition to the top level model behavior decisions already mentioned, a number of assumptions and decisions were made with regards to the technical accuracy of the simulation prior to developing the model. These covered such areas as the menu being modeled, food item locations, serving line processing stations, resources required for serving the meal, the characteristics of these resources, and personnel characteristics. The following subsections identify and document these decisions, and provide the reasoning behind them.

Serving Line Layout. The starboard mess line was modeled based on a CAD2 drawing provided to the project team. This drawing served as the template on which the simulation model is built. As a result the simulation model was created to scale with the 3-D elements displayed located above the actual footprints of the objects they represented.

Crew Size. The crew consisted of both the ship's enlisted crew (429) as well as the maximum number of embarked troops (597) that the ship was designed for. With only the starboard mess line modeled in the simulation, the number to be served by this mess line is 513, or half of the total complement.

Mess Deck Capacity. The mess deck was also modeled as half of that identified in the ship's drawings. As a result the baseline simulation model contains only 84 seats.

Mess Specialist and Food Service Attendant Stations and Duties. The mess line support personnel for which utilization rates were determined are identified in Table IV along with their primary duties and location.

Crew Member Identification	Primary Duties	Primary Location
FSA#1	Hotwell Server	Galley behind hotwells 2, 3, 4
FSA#2	Hotwell Server	Galley behind hotwells 5, 6, 7
FSA#3	Hotwell Bin Reloader	Galley
FSA#4	Utensil Bin Reloader	Scullery
MS#1	Grill Operator	Galley behind grill
MS#2	Grill Operator	Galley behind grill

Table IV. Serving Line Manning Requirements

Since the grill is used only to cook chicken breasts for dispensing from the hotwell, only one cook is required for use during the simulation run. As a result MS#1 is not utilized during this study.

Traffic Flow. An equally important element of the simulation model is the traffic flow of the troops and crew members in the serving line, as well as the interaction between them and the crew members on duty in the mess area. To account for these actions a number of assumptions were made. Because one of the basic goals of this project was to determine the throughput of the mess line, it was decided early on that the simulation model would not take into account the staggered arrival process of personnel for meals as would actually occur aboard ship. Specifically, early meal for watch reliefs, head of the line privileges for first class, and late arrival of off-coming watch standers were not modeled. The model also assumed a steady flow of personnel from the starting point after the simulation run began for a worst case scenario. The starting point is the starboard vestibule forward of the bulkhead at frame 47½, which contains the starboard ladder well. These assumptions, in addition to providing an easy method for determining the throughput of the mess line, and the steady flow rate, also helped to simplify the complexity of the model for this pilot study.

In order to accommodate the interaction of the model elements during any given simulation run, a number of other assumptions regarding the traffic flow were also made. These assumptions and the factors that are applied in the simulation model are identified below.

- Width of 95 percentile man = 0.56 m (1.8 ft). [3]
- Personnel walking speed = 1.16 m/sec (3.81 ft/sec). [3]
- Minimum spacing of personnel in the mess line = 0.8 m (2.7 ft) (distance from leading edge of one person to the leading edge of the next).
- Mess line path width = 0.6 m (2 ft).
- Personnel will stay in the mess line until entering the mess deck.
- 60% of the crew will use the starboard mess deck entrance, and 40% will use the centerline entrance
- Maximum capacity in the mess deck = 84 personnel
- Each troop or crew member will use the mess deck for approximately 21 minutes (currently set at constant value).
- The starboard serving line began at the starboard water tight door at frame 47½ from the inclined ladder vestibule and proceed aft.
- The line, as it moves aft, is routed along the outboard bulkhead until frame 60 where it then turns inboard and forward to pass along the serving line.
- If the scullery FSA is reloading a utensil dispenser, then the crew in the mess line will not be able to select that type of utensil until the FSA is finished reloading the dispenser
- The hotwell server assists the hotwell reloader for 12 seconds when one of his or her hotwells is being reloaded; the first hotwell server also assists the reloader with the soup hotwell.
- When the hotwell server is assisting the hotwell reloader, the mess line is unable to select food from that station until the hotwell server is done.
- A Mess Deck Master At Arms will be positioned at the end of the serving line to control access to the mess deck.

The reason the crew member width was based on the width of the 95 percentile man is because it provides an accepted figure that represents the higher end of the range that could possibly be experienced aboard ship. Except for helping to identify the required width of the mess line traffic path, this figure has no other impact on the simulation model or its results.

The mess line flow path was modeled in accordance with the drawings, and as indicated above. In addition, fourteen process or action stations were placed along its length. These stations identify locations where actions are performed by the crew member traveling along the path. As an example, at Station 2, the menu board, each crew member pauses to read the menu. The length of the pause is based on a triangular distribution between 0 and 5 seconds with the mode at 2 seconds. A description of each station is provided in Table V.

Station	Description	Station	Description
1	Mess Line Entrance	8	Hotwell 1
2	Menu Board	9	Hotwell 2, 3, 4
3	Tray Pick Up Point	10	Hotwell 5, 6, 7
4	Plate Pick Up Point	11	Dessert Pick Up Point
5	(For future use)	12	Bread Pick Up Point
6	(For future use)	13	Starboard Mess Deck Entrance
7	Bowl Pick Up Point	14	Centerline Mess Deck Entrance

Table V. Mess Line Routing Sequence

As indicated in Table V, the trays, plates, and bowls were picked up by the person as he or she passed the appropriate station. Crew members were not expected to pick up utensils unless they used it later for the food they were selecting. In other words, unless the crew member wanted soup, or their vegetables in a bowl, they did not pick up a bowl when they reached Station 7. If they wanted both, they selected two bowls.

Only three other items, in addition to the utensils, were modeled as being self served by the personnel as they passed through the line. These items were the soup, dessert, and bread menu items.

The FSA associated with the scullery work was modeled as following a path that primarily consisted of a straight route from the scullery out the centerline entrance of the mess deck, and then down the starboard passageway to the tray dispensers and into the galley. This path was used whenever the FSA was required to restock the trays, dishes, or bowls in the starboard serving line, and also for the return trip to the scullery. It was assumed that both the scullery FSA and the crew members in the mess line avoided each other as they passed, so there were not any delays in the process flow of either entity being modeled due to congestion.

Menu. A dinner menu representative of an actual dinner that might be served aboard ship was chosen for simulation. This menu was selected from the NAVSUP Pub. 421, Food Service Operations, January 1994 [4], and is identified in Table VI along with the specific hotwell or other designated area of the serving line from which the indicated menu item is served. Note: The extended serving line is not modeled and therefore the salad and beverage area are not included in the logics or graphical representation of the starboard serving line.

Location	Menu Item
Hotwell 1	Pepper Pot Soup
Hotwell 2	Grilled Chicken Fillet
Hotwell 3	Tomato Meat Loaf
Forward Half Hotwell 4	Chicken Gravy
Rear Half Hotwell 4	Tomato Sauce
Hotwell 5	Au Gratin Potatoes
Hotwell 6	Steamed Rice
Forward Half Hotwell 7	Seasoned Mixed Vegetables
Rear Half Hotwell 7	Steamed Zucchini
Cold Food Counter	Fruit & Dessert Bar
Cold Food Counter	Hot Pan Rolls
Extended Serving Line	Garden Vegetable Salad

Table VI. Menu Item Locations

Food Selection. In addition to selecting the menu that would be modeled, it was also determined that an appropriate distribution would need to be developed that would reflect the food selection distribution of the troops and crew. The meal selection distribution follows:

- 40% Soup
- 45% Chicken
- 45% Meat Loaf
- 40% Au Gratin Potatoes
- 40% Rice
- 40% Seasoned Mixed Vegetables
- 40% Steamed Zucchini
- 50% Dessert
- 50% Bread

As a result of this distribution 10% of the crew will not select either entree, 20% of the crew will not select either starch item, and 20% of the crew will not select either vegetable item. This distribution also allows for a 0.4 % chance that a crew member will not select an entree, starch, nor a vegetable; if this occurs soup and bread will be selected as default.

Serving Size. The next step in the development of the model consisted of determining the serving size for each item and the maximum amount of servings that would be present in the serving area (in most cases the hotwell).

The maximum number of servings that were allowed in the simulation were dependent on the type of serving container being used. Except for the dessert and bread items, all items were modeled as being served from a hotwell. The model included two different types of hotwell pan. The nominal size and fluid ounce capacities of these two types were identified in the book titled *Commercial Kitchens* [5], and are: 12” x 20” x 2 1/2” for 240 oz capacity, and 12” x 20” x 4” for 464 oz capacity.

The serving capacity of each hotwell was dependent not only on the size of the individual hotwell, but also on the menu item being served from it. The serving size of the menu item, the hotwell pan size it was in, and the maximum number of servings contained by the hotwell is identified in Table VII for each item.

Menu Item	Serving Size	Hotwell Capacity (oz)	Servings/ Hotwell
Pepper Pot Soup	8 oz	464	58 servings
Grilled Chicken Fillet	15.25 sq in	240 or 240 sq in area	15 pieces/layer or 48 servings
Tomato Meat Loaf	5 oz	240	48 servings
Chicken Gravy	2 oz	232	116 servings
Tomato Sauce	2 oz	232	116 servings
Au Gratin Potatoes	6 oz	464	77 servings
Steamed Rice	3 oz	464	154 servings
Seasoned Mixed Vegetables	5 oz	240	48 servings
Steamed Zucchini	5 oz	240	48 servings
Fruit & Dessert Bar	N/A	N/A	N/A
Hot Pan Rolls	N/A	N/A	N/A
Garden Vegetable Salad	N/A	N/A	N/A

Table VII. Menu Item Serving Size and Hotwell Capacity

For the pilot program, the fruit, dessert, and hot rolls were modeled as being unlimited in quantity, and therefore did not require tracking or restocking. The salad bar is not included because it was decided at the onset of this project that the salad bar would be located in the mess deck, and that the mess deck would not be modeled in any detail.

In working these elements into the logic of the simulation model, it was assumed that, except for the soup, all hotwell items would be served by one of the two FSAs behind the hotwell serving area. It was also determined that at various times throughout the simulation any one of these hotwells might require restocking. This can be verified by simply comparing the hotwell serving sizes indicated in Table VII to the crew and troop size being modeled (i.e. half the ship’s crew and troop complement, or approximately 513 crew members). As a result, a hotwell restocking process was incorporated into the model. This restocking process involves a FSA working in the galley, and requires him or her to manually replace the hotwell.

The actual restocking process is initiated when the quantity contained within a hotwell reaches a specific level. For this model it was determined that this level would be at 10% of the initial quantity. This assumption is in close accordance with the process that actually occurs aboard ship, where the pans are

usually never completely empty before a replacement pan is placed in the serving line. It was also decided that any left over servings from the old pan would be added to the amount contained in the new pan when the restocking process occurred.

In addition to these assumptions, it was also decided that the initial amount in an original or replacement hotwell would be either 90% or 75% of the maximum capacity depending on the type of item in the hotwell. For liquids 75% was used, while 90% was used for solids. This margin in hotwell capacity was intended to: prevent items from falling or sloshing out of the hotwell pan as it or the ship moved; and prevent spills from occurring due to the addition of the leftovers to the hotwell replacement pan.

The serving amounts identified in Table VII were therefore adjusted. It was also decided that the replacement amount for a hotwell would be equal to its initial amount of servings. Although these factors are identical, in the simulation model's code they are independent variables and may be changed by the user when desired.

Utensil. The utensil dispensers modeled in this simulation are based on the selected ship design drawing obtained by the project team. In that design drawing it was identified that the tray, plate, and bowl dispensers would be located along the mess line, and the silverware would be obtained from above the tray dispensers. It was also specified that the trays would be of the non-segmented or flat type, and that the silverware would be obtained when a tray was. Because of this the silverware and trays are modeled and tracked as one unit.

In working these elements into the logic of the simulation model, it was also assumed that 40% of the crew would want to use a bowl for something other than soup. In this model this other use was to hold vegetables. Another area of concern that was addressed by the model was the restocking of these utensil dispensers. Since none of the dispensers have an initial quantity large enough to support the troop and crew size being modeled the restocking process for the dispensers was also incorporated into the model. This restocking process involves a FSA working in the scullery, and requires him or her to manually carry the restock load from the scullery to the appropriate dispenser. Mobile carts cannot be used because the scullery has a 22.9 cm (9 in) sill around it to prevent water from entering the mess area.

The actual restocking process is initiated when the quantity contained within a dispenser reaches a specific level. This level along with the initial amount and refill size for each dispenser are identified in Table VIII. Note: Refill size indicates load size carried by the scullery FSA.

Utensil Name	Initial Amount	Refill Point	Refill Size
Tray Dispenser 1	150	50	25
Tray Dispenser 2	150	50	25
Plate Dispenser 1	72	24	12
Plate Dispenser 2	72	24	12
Bowl Dispenser 1	36	12	12
Bowl Dispenser 2	36	12	12
Bowl Dispenser 3	36	12	12

Table VIII. Utensil Dispenser Refill Information

Once the restocking process is initiated for a utensil dispenser, the scullery FSA will make as many trips as required in order to bring the utensil dispenser's amount equal to, or above, its refill point.

Process Time Assumptions. In order to create a simulation model that reflected the actual mess line process as accurately as possible, process times were required to be associated with each specific process being modeled in the simulation. Because of the inherent variability of the time associated with any of these processes, distributions were also attached to some of them in an attempt to more accurately reflect what would occur as the process is repeated throughout the duration of the simulation. Unfortunately, due to the inability to conduct time studies on which to base these distributions, few of the process time durations used are statistically based. As a result assumptions were made regarding the time required for crew members to perform their duties and conduct the modeled tasks. The times associated with the FSAs and MSs performing their tasks are identified in Table IX. The soup, dessert, and bread are self served, and MS#1 is not modeled.

Serving Time (FSA#1 & FSA#2)	**Hotwell Bin Refill Time (FSA#3)**
Chicken = 5 sec	Hotwell Reload Time = 30 sec
Meat Loaf = 5 sec	**Utensil Bin Refill Time (FSA#4)**
Chicken Gravy = 5 sec	Scullery load pick up time = 5 sec
Tomato Sauce = 5 sec	Scullery load drop off time = 5 sec
Au Gratin Potato = 5 sec	**Chicken Prep Time (MS#2)**
Rice = 5 sec	Grill time = uniform 10 ± 1 min
Seasoned Mixed Vegetables = 5 sec	for 43 chicken breasts
Steamed Zucchini = 5 sec	Placement in hotwell = uniform
Hotwell Reload Assist Time = 12 sec	5.75 ± 1 min for 43 chicken breasts

Table IX. Resource Utilization Times

The processes for which time lengths are associated with the personnel transiting the serving line are identified below.

- Menu read: triangular distribution 0, 2, 5 seconds.
- Tray pickup: constant distribution 2 seconds.
- Plate pickup: constant distribution 2 seconds.
- Bowl pickup: constant distribution 2 seconds.
- Desert pickup: constant distribution 2 seconds.
- Bread pickup: constant distribution 4 seconds.
- Mess deck use: constant distribution 21 minutes.

The mess deck utilization of 21 minutes is based on the standard design factor of 18 minutes of use per person with an additional 3 minutes to account for the time taken to get his or her drink and salad, find a seat, and clear the area after finishing eating.

Graphics

In addition to creating the logic for the simulation model, 3-D graphical images were also created so that the actual process flow of the starboard mess line could be visualized. These graphical images, created within the simulation software product AutoMod, display the changing status of the model during the simulation run. The frequency at which these graphical images

are updated can be specified by the user, but by default is every 1 second of simulated time. These 3-D images represent the bulkheads and equipment that are pertinent to the portion of the serving line mess area being simulated. The equipment is approximately equal to its real life size, and is positioned as indicated on the CAD2 drawing. The primary use of the visualization capabilities of these types of simulation projects is to visually verify the accuracy of the process being modeled, and to visually convey the process being simulated to someone unfamiliar with it. Sample screen prints of these images are shown in Figures 1 and 2.

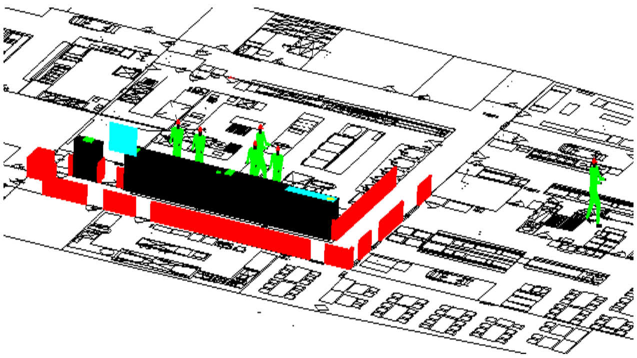

Figure 1. Serving Line Overlaid On CAD Drawing

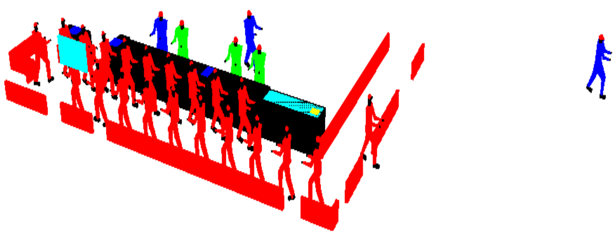

Figure 2. Starboard Serving Line In Use

Simulation Run Results

Prior to discussing the results of the simulation analysis of the selected ship's starboard mess line it should be emphasized that the results obtained are based on the assumptions and conditions modeled. Although these assumptions and conditions were judged to be reasonable they were not validated. Therefore until validated data is obtained, the results and conclusions drawn from this analysis are only applicable to this model.

Using the simulation software, the ship's starboard crew mess line was modeled in accordance with the information and assumptions presented in this paper. Due to the deterministic nature of these assumptions (i.e. all but two time delays were constant numbers), only one simulation run was performed for data collection. The primary reason for this is that deterministic models show no variance between individual runs; the event sequencing, lengths, and interactions are by definition predetermined. Except for the mess cook grilling the chicken to refill the chicken hotwell, and each crew member pausing at the menu board in order to read it, the model developed for the ship's starboard crew mess line was deterministic. This classification was quantified during the model testing stage when a number of runs, utilizing various starting points on the random number stream, as well as a different type of random number stream, were made and analyzed. The results of each test run were identical, i.e., the overall time length for serving the crew and troops did not change between runs.

The primary reason for the deterministic nature of the assumptions used in this model is due to the unavailability of data on which to accurately base and select the form of the statistical distributions. Modifications however, can be made to the model when this data becomes available, thereby implementing the statistical distributions and obtaining a stochastic process.

In addition to simulating the use of the starboard mess line for a half mess deck capacity of 84 seats, eight other simulations of increasing mess deck capacity were also made. Each of these runs was performed under the exact same constraints and conditions as the original run except for the factor identifying the mess deck capacity. This factor was increased in increments of five, until a capacity of 119 seats was reached, and then set at infinite. The overall objective of this analysis was to determine the effect of increasing the number of seats in the mess deck on the crew feeding time, as well as the utilization rates of the personnel supporting the mess line. The final run at infinite seating capacity was performed in order to evaluate the true efficiency of the serving line without any seating constraints being imposed upon it. Specifically the mess deck wait delay constraint, symbolizing the Mess Deck Master At Arms control of the mess deck access when all mess deck seats are occupied, was negated.

Simulation Run Time. The total serving and messing time associated with each run is identified in Table X, along with the maximum duration spent waiting by any one crew member during the messing process. The total serving and messing time represents the amount of time required for all 513 troop and crew members to process through the starboard serving line and eat their meals in the mess deck. The mess deck wait process symbolizes the interaction and effect of the Mess Deck Master At Arms on the mess line flow as he or she controls access to the mess deck when all seats are occupied. The maximum mess deck wait duration times displayed in Table X identify the longest time spent by any one crew member waiting to enter the mess deck. The specific crew member that had to wait is identified by Crew ID Number. The Crew ID Number represents the identity of the troop or crew member being processed through the simulation, i.e. Crew ID Number 1 represents the first person in line, while Crew ID Number 215 represents the 215th person in line. Note: The times in Table X have been rounded off to the nearest second.

Half Mess Deck Capacity	Process Information		
	Total Serving and Messing Time (hrs:min:sec)	Maximum Mess Deck Wait Duration (min:sec)	Crew ID #
84	2:31:37	6:18	85
89	2:28:44	5:26	90
94	2:27:43	4:25	95
99	2:26:41	3:40	100
104	2:25:53	2:36	105
109	2:25:20	1:43	110
114	2:23:36	0:52	115
119	2:24:11	0:05	145
Infinite	2:24:11	0:00	N/A

Table X. Process Information

As can be seen by examining Table X, and as would be expected, the influence of the mess deck seating on the overall mess line performance decreases as the seating capacity of the mess deck increases. In fact at 119 seats the maximum mess deck wait delay experienced by any crew member is only five seconds, a negligible amount.

A similar conclusion might also be drawn from examining the Total Serving and Messing Times, presented in Table X, for the nine conditions modeled. But as can be seen in Table X, the process flow time decay rate does not produce a smooth transition between runs as might be expected. The dip in the decay rate, shown for a half mess deck seating capacity of 114 seats, indicates that the interaction between the mess deck seating capacity and the processes occurring in the serving line is the most efficient at a half mess deck seating capacity of 114 seats.

Serving Line Throughput. Another goal of this project was to determine the number of personnel passing through the serving line (i.e. completing all processes through station number 12) in the first twenty-one minutes. This time span, which equals the time spent by a troop or crew member using the mess deck, was examined in order to obtain a throughput that was reflective of the serving line and its inherent characteristics, and not of the serving line plus the constraints imposed upon it by the seating capacity of the mess deck. The results are identified in Table XI.

Half Mess Deck Capacity	Number Served
84	85
89	90
94	95
99	100
104	105
109	110
114	114
119	114
Infinite	114

Table XI. Number Of Personnel Served In The First 21 Minutes

As can be seen by examining Table XI, the maximum serving line throughput for the first twenty-one minutes of simulation run time is 114 crew members. Before identifying exactly when this point is reached though, some explanation of the data presented needs to be made. The serving line throughput, as shown in Table XI, is one person greater than the mess deck capacity for capacities of 109 people and below. The reason for this is that the delay imposed by the Mess Deck Master At Arms when the mess deck is full is imposed immediately after a crew member has passed through the serving line (i.e. finished processing through station number 12). As a result, although crew member number 85, using a mess deck capacity of 84 as an example, passes through the serving line in under twenty-one minutes, he or she has to wait for a certain amount of time prior to proceeding into the mess deck. As previously mentioned this wait signifies the amount of time required before a seat opens for him or her to use. Because this wait is imposed in the physical location of the last station (a location where a food service process occurs), the serving line throughput halts until this person is able to proceed into the mess deck. Using this as the basis of the interaction that is occurring in the simulation model at the end of the serving line, it can be deduced that the serving line throughput reaches a maximum at a mess deck seating capacity of 113 seats.

Support Personnel Utilization. Identification of the utilization rate for the mess line support personnel was another important goal of this project. The determination of the utilization rates not only helps to better understand the interactions being simulated, but also provides information related to manning reduction opportunities. The utilization rates of all of the support personnel used in this model are identified in Table XII. The location and duties of these support personnel are defined in Table IV. It should also be mentioned that in Table XII, the resource utilization factor has been rounded off to the nearest tenth of a percent and is determined by the following equation:

$$\text{utilization} = \frac{\text{total claims * average time per claim}}{\text{total clock time}} \quad [6]$$

	Half Mess Deck Capacity								
	84	**89**	**94**	**99**	**104**	**109**	**114**	**119**	**Infinite**
FSA#1	51.2	52.2	52.6	52.9	53.2	53.4	54.1	53.8	53.8
FSA#2	46.5	47.4	47.7	48.1	48.3	48.5	49.1	48.9	48.9
FSA#3	11.2	11.4	11.5	11.5	11.6	11.6	11.8	11.7	11.7
FSA#4	50.7	52.3	53.3	53.6	53.4	53.6	54.3	53.3	53.3
MS#2	33.8	33.6	33.9	34.4	34.0	35.6	35.0	35.0	35.0

Table XII. Resource Utilization Rates In Percent

Except for an occasional small deviation, the support personnel utilization rates presented in Table XII behaved as expected, increasing as the mess deck capacity, and therefore serving line throughput, increased, and the overall process flow or simulation run time decreased. It should also be noted that the highest utilization rate for the FSA support personnel occurred at a mess deck seating capacity of 114 seats. This is as expected since, as previously discussed, the interaction between all of the

processes being modeled in the simulation was the most efficient under this mess deck seating condition.

Mess Line Simulation Conclusions

Based on the results of the simulation runs many conclusions can be drawn on the modeled galley mess line design. The first is that increasing the number of seats has a minimal effect on reducing the overall serving and messing time. Secondly, the mess deck seating capacity does have a large effect on the mess deck wait time imposed by the mess deck master at arms when all mess deck seats are occupied. These conclusions are supported by the data shown in Table X.

Other conclusions (based on the assumptions used) that can be drawn to demonstrate the utility of the model include:

- The length of time required to serve and feed the entire crew and troop complement with both the port and starboard serving lines is approximately:
  - 2 hours and 32 minutes for the baseline design mess deck capacity of 168 seats
  - 2 hours and 24 minutes for a mess deck with infinite seating capacity
- The combined overall average serving line flow rate based on serving the entire complement of crew and troops using both serving lines is:
  - 8.0 people per minute for the baseline design mess deck capacity of 168 seats
  - 8.4 people per minute for a mess deck with infinite seating capacity
- The number of people that can be served in the first twenty-one minutes from both serving lines is:
  - 170 people for the baseline design mess deck capacity of 168 seats
  - 228 people for a mess deck with infinite seating capacity
- At an 11 to 12 percent utilization rate, the FSA responsible for hotwell restocking is a good candidate for manning reduction assuming no additional duties than those modeled are actually assigned to this person.
- At a 50.7 to 53.3 percent utilization rate for one serving line, the scullery FSA is a good candidate for a manning increase assuming that this person is solely responsible for restocking the utensil dispensers in both the starboard and port serving lines.
- The serving and messing time performance curves indicate that the interaction between the serving line and the mess deck is most efficient at a mess deck seating capacity of 228 seats.

The modeled results also indicate that the baseline serving line may be over designed for the actual environment in which it will operate. As identified above, the maximum throughput that can be obtained for the current design, as modeled with a mess deck capacity of 168, is 170 crew and troop members in the first 21 minutes. This raises several questions concerning the serving line design as modeled. These questions include:

- Might less capable and less expensive serving line equipment result in a throughput more commensurate with that imposed by the mess deck seating capacity constraint?
- Can the Mess Deck Master At Arms duties and responsibilities be eliminated if the serving line was designed with a throughput matching that imposed by the mess deck seating capacity constraint, and therefore allowing a constant flow of personnel into the mess deck? This is a possible manning reduction opportunity.

The most important conclusion is that the time required to serve and feed the crew and troops can be significantly reduced only by addressing both the mess deck seating capacity constraint and the serving line design and process interactions together.

It is again emphasized, however, that the results obtained and conclusions mentioned above are based on input data assumptions that were judged to be reasonable. The specific purpose of this pilot program was to demonstrate the utility of process flow simulation tools.

VISUALIZATION TECHNOLOGY

Virtual Ship Production

This portion of the paper summarizes the work performed using visualization technology to simulate the production process of a hypothetical amphibious class ship. To assist in this effort a detailed master construction schedule of the ship was developed using the *LX Preliminary Design (PD) Generic Build Strategy Study* as a reference. The production process was modeled by scheduling the ship's identified blocks through the fabrication, assembly, and erection phases of construction. Linkages from the schedule to the visualization tool were developed to enable the schedule to drive the visualization sequence for the erection phase. Certain long lead material items are also included in the schedule and, therefore, are part of the visualization.

In order to keep the task generic in nature, a series of twelve staging areas are used to queue blocks after completion of assembly and prior to erection. The visualization illustrates the erection process from the staging area forward to final ship completion. The screen templates track the elapsed time in weeks for an easy to gage real time status of the ship construction process. Various other useful templates are available to customize the software.

The results of the task provide a good first step in the evaluation of the early stage design/producibility interface. The visualization methodology used can be developed as a shipyard specific tool to evaluate ship acquisition proposals, and for project management of the acquisition process. Because the methodology used can be customized and expanded upstream into the total construction process, the scheduling/visualization integration capability of the shipyard's various processes is unlimited. Another unique aspect of this task is that the whole process is Personal Computer (PC) based with reasonably priced commercially available software products. This allows the concept to be used without special hardware or major software investment. Also, as an early stage design tool, this process is easily conveyed on a network setup to management, systems engineers, technical leaders, and ship designers. This concept also allows for

evaluations early on in the design process and at the early stage of the contract design phase.

The block break configuration was developed by importing CAD files from the ship computer model. Because of this, it is easy to develop and simulate alternate build strategies, and visually evaluate engineering changes and their affects on the producibility of the ship. The data produced will also allow the use of “what if” scenarios to evaluate schedule alternatives and ship construction sequences, and provide the ability to play the actual erection sequence out as a visualization.

Every effort was made in the development process to keep the process as simple as possible and user friendly. Also, an objective was to have the programs run on available hardware configurations without major added cost to the end user.

Software Selection

The software products selected for use in the development of the project’s **Virtual Ship Production** product are as follows: Microsoft Access Version 2.0, Microsoft Project Version 4.0, Autodesk 3D Studio Release 4.0, and Microsoft Visual Basic Version 4.0. The criteria used in choosing these products included platform portability, cost, performance, and data exchange capability. Microsoft Visual Basic was selected as the programming language with which the links and interfaces between each of these products were built.

Database Software. The selected software was chosen to support the database requirements of the project because of the product’s following four characteristics:

- It has become a leading PC based relational database software.
- It provides a smooth data pipeline between itself and the chosen project scheduling software.
- It has an exceptional report generator.
- It possesses a common programming language with the other software products.

In addition to the above four characteristics, the software was also chosen because it and the project scheduling software have mutual import/export capabilities. This can be done in a native file format as well as several intermediate format styles. The native file capability means that project scheduling software can write directly to the database software and then read back the data into a project file.

The report writer associated with the database software uses the powerful capabilities of query by example, multiple data sources, and a wide range of data formatting and conversion functions. All of this along with cross-tab and free form report formats makes the database report generator a logical choice for this project.

Project Scheduling Software. The project scheduling software was selected as the project management software for the following reasons:

- Affordable to second tier shipyards;
- Pert network capability;
- Common data structure;
- Common programming language; and
- Interfacing/Object linking and embedding (OLE) capability with the other software products.

Visualization Software. The visualization software product for this project was chosen because of the following product capabilities.

- COTS software.
- PC compatibility.
- Capability of providing an animation sequence that could be viewed on the operator’s PC.
- 3-Dimensional graphic environment to adequately show ship’s block break arrangement and assembly/build strategy sequence.
- Capability of interfacing with scheduling and database management programs in order to accurately represent the positioning and sequence of the identified ship blocks during the “virtual” construction, assembly, and erection phases.
- “Keyframing” programming language that allows easy control of animation by reading, line by line, an ASCII datafile output from another program. Direct input of movement information into the 3-D model environment is thereby performed.
- Command line rendering capability, which allows for easy access and processing from within another user interface, or shell program.
- Single frame, and range of frames, rendering capability which allows the user to quickly render and view any particular moment in the animation sequence without having to render the entire sequence. This saves on rendering time. (Note: Rendering is the process whereby the visualization software creates the graphical image being portrayed.)
- High quality rendering modes include photo-realistic still scene rendering, and variable quality and size rendering. These modes allow for the production of single frame still shots for printing and display, as well as for control over the disk space and rendering time requirements of animations. Flat, Gouraud, Phong, and Metal-shading modes also support any range of image resolution, thereby giving the user control over animation output to allow for any system disk space or time constraint consideration.
- Network rendering options that allow the distribution of rendering tasks to other PCs running this software in order to reduce the overall rendering time of the animation sequence.
- Still images can be saved as color .GIF, .JPG, .TGA, .TIF, .BMP, and .JPG picture file formats that are widely used throughout various PC graphics packages and software applications.

In addition to these factors the product was also chosen because it is a well rounded visualization software package that is used by a broad range of professionals (i.e. videographers, architects, engineers, etc.) and has a large product support base.

Integration Software. The integration software was chosen for this project for the following reasons:

- It is a capable Windows application development environment,

- It can utilize data from many sources in many formats, and
- It can programmatically process data.

With the integration software, the developer can organize and design screen-based forms that present the data of a project in logical and coherent ways. Industry standard controls can be used, such as drop down lists, buttons and menus. In this project, the integration software allowed the developers to display and deal with the **Virtual Ship Production** project data in a highly customized, more efficient way.

The integration software is capable of complete, broad based data manipulation. It can read and write data from numerous sources and it has extensive internal capabilities for formatting and converting data. In this project, the integration software is used as a data intermediary that moves data between applications, displays the data, and processes it for use in an animation program.

The integration software provides a rich, extensible programming language and as such it is used in this project to process the data it can reach. This processing includes converting project data into a sequential list of events, scheduling the list of events to follow a bin filling scheme utilizing variable resources, and generating the data elements to record the event. While processing, the integration program checks for errors, keeps statistics on resource usage, and converts the data format to one that can be used by the animation program. The information is then output to a file that is used as input for the animation.

Product Model Development

Platform Selection. As previously alluded to the goal of this project was to develop a tool that offers the following capabilities/features:

- Uses Simulation Based Design (SBD), and High Performance Visualization (HPV) technology to model ship production breaks and erection sequence.
- Provides the capability of incorporating CAD Library information for machinery and outfit components, and establishes linkages with production schedules such as erection and material ordering schedules.
- Incorporates engineering interfaces which provide a user friendly environment for this effort.

With these overall goals of the project tasking in mind, the basic objectives of the project's product, **Virtual Ship Production**, were further refined. As a result it was determined that the end product should provide the following features and capabilities:

- Presentations for progress reviews.
- Product platform portability (i.e. PC based with COTS software).
- Progress tracking with color presentations for shipyard internal use.
- Process lane resource planning, and throughput/bottleneck identification.
- Internal management presentations for "what if's" at the vice president level and higher.
- Detail tracking of completion at the workstation or gate level with process lane/work station simulations.
- An animated demonstration of the erection sequence for production planners, superintendents and foremen as a training tool.
- Interactivity allowing the user to modify the schedule to reflect problems or changes that occur during the ship construction period and identify the corresponding results that occur.
- A production schedule that links the fabrication, assembly, and erection of the ship's blocks with the ordering, inspection/preparation, and landing of equipment, and other important milestones.
- The ability for the user to evaluate different production schedules and choose the one that best fits his or her requirements (i.e. optimum construction time, finance requirements, work load leveling, etc.).

Master Construction Schedule Development. The development of a detailed master construction schedule was accomplished with the above mentioned features and capabilities of the finished product **Virtual Ship Production** in mind. As mentioned the information contained within the *LX Preliminary Design (PD) Generic Build Strategy Study* was used as a reference. Specific items of interest contained within this study included:

- Block Break Plan
- Key Event Schedule
- Master Construction Schedule
- Hull Erection Schedule
- Typical Long Lead Time (LLT) Schedule
- Typical LLT items
- A preliminary Master Equipment List (MEL)

The Master Construction Schedule created for the project therefore was in a large part based upon the information contained within the *LX Preliminary Design (PD) Generic Build Strategy Study*. The work done in developing the new Master Construction Schedule was initiated on project scheduling software, and later transferred to the database software via the front-end interface developed for this project.

Identification Of Tasks/Events. Many resources were utilized in identifying the tasks or events that would be tracked by the new Master Construction Schedule. In addition to the information contained within the *LX Preliminary Design (PD) Generic Build Strategy Study*, historical ship construction information was used as well as the shipyard experience of some of the project team members was used.

Based on the information culled from these sources it was decided that as a minimum the Master Construction Schedule would be centered around the following production processes, or areas of concern:

- Ship Construction Milestones
- Hull Construction

- Outfitting

These areas of concern, or production processes, can be further broken down into sub-elements as identified in Table XIII.

Milestones	Hull Construction	Outfitting - Equipment
– Contract Award	– Fabrication	– Ordering
– Detail Design	– Assembly	– Receipt, Inspection, & Preparation
– Start Construction	– Erection	– Landing
– Lay Keel	**Note: The above subdivisions can be further classified by:**	
– Launch	– Zone	
– Builders Trials	– Sub-Zone	
– Delivery	– Block	

Table XIII. Minimum Contents Of A Master Construction Schedule

Milestone/Miscellaneous Events. A number of milestones and miscellaneous events are involved in scheduling and managing a ship construction process. Although all of these events should be used in developing a ship's Generic Build Strategy and overall production schedule, only ten of them are identified and visually displayed by the project's associated graphics package. These ten events are identified below:

- Contract Award
- Detail Design
- Start Construction
- Lay Keel
- Start Superstructure Erection
- Launch
- Dock Trials
- Builders Trials
- Acceptance Trials
- Delivery

These events were chosen for the following reasons:

- The nature of the event lends itself to being easily shown during the visualization of the ship production process;
- The scheduling and completion of the event, or task, greatly effects the overall production process;
- The event, or task, can be easily used to gauge the progress of production; and
- There is a distinct start, stop, or time period associated with the task, or event.

Hull Construction. The shipbuilding process currently utilized by modern shipyards is based upon the principle of Group Technology (GT). In addition to being a philosophy of grouping products based on similar production characteristics, GT is also used as an umbrella which covers a number of other production methods. The Hull Block Construction Method (HBCM), used during the structural construction of ships, is one of the methods which falls within the domain of GT. In HBCM, ship structures are incrementally built up from interim products until the final product, a ship's structure, is achieved. Depending upon the design, and the production capabilities of the shipyard, this method of ship construction can employ up to seven different manufacturing levels. These levels are characterized primarily by the stage of production in which they are found, and can also be further classified into three groups based on their predominant production aspects.

For the purposes of this project though, the work flow path was modeled as consisting of the following four basic steps:

- Block Fabrication
- Block Assembly
- Crane Transfer
- Block Erection

There were a number of reasons for this reduction in the detail of the HBCM work flow path, including the fact that it is the Block, and not necessarily the interim products (i.e. semi-block assembly, sub-block assembly, part assembly, and part fabrication), that is the key structural element in the construction of a ship. In other words, the ship's Block Breakdown, and the resultant production aspects of each Block, determine the work flow that will be experienced during the ship's construction process. Other reasons for minimizing the amount of detail concerning the ship construction process that is tracked and visually presented in this project include:

- The Master Construction Schedule contained within the ship's Preliminary Build Strategy identified the structural start and stop events associated only with block fabrication, assembly, and erection.
- Shipyard Master Construction Schedules normally track only the following structural events: block erection, block assembly, and block fabrication. (Note: Sometimes these latter two events are tracked as a single event.)
- The three events tracked are directly germane to the erection of the ship

The crane transfer task has been added to the revised HBCM work flow path in order to represent the transfer by crane of the blocks from the staging area to the erection site.

For this project the hypothetical ship's hull construction process is modeled as consisting of 184 blocks. Each of these blocks will be individually identified and tracked by the project's product model.

Outfitting. The outfitting process in ship production is an extremely complicated one that can also, if not properly managed, be very time extensive. Like HBCM, there is also an outfitting method specifically associated with Group Technology. This method, called the Zone Outfitting Method (ZOFM), incorporates the same principals and philosophies of Group Technology that HBCM does. In ZOFM, the outfitting process is broken down into a sequence of steps that indicate the process taken in landing equipment aboard ship. There are six different stages, or manufacturing levels associated with the Zone Outfitting Method.

As with HBCM, the outfitting process being modeled in this project is an abbreviated form of ZOFM. Unlike the original process, which contains six different manufacturing levels, the revised outfitting method only identifies three manufacturing levels. These levels are identified in Table XIV, and are meant to only identify the major process associated with placing equipment onboard the ship and not describe the entire process in detail. This reduction in the amount of detail being represented was done in

order to develop a management tool that contains a similar level of detail to that normally associated with the upper management level in a ship construction program.

Outfitting Level - Equipment	Description
Ordering	Point of time at which the item is ordered.
Receipt, Inspection, and Preparation (RIP)	Span of time covering the processes associated with the item's receipt, inspection, and preparation for landing in the block or ship.
Landing	Process of actually placing the item in the block or ship.

Table XIV. Outfitting Manufacturing Levels Modeled

For the purposes of this project, it was decided to model only the outfitting process associated with some of the ship's critical equipment and/or long lead time (LLT) items. The selected items, and the blocks with which they are associated are identified in Table XV.

The relationship that the critical equipment/LLT items being modeled in this project have with the phase of ship construction in which they are landed is identified in Table XV. In this table the *After Block Erection* phrase signifies on-board outfitting, and indicates that the landing of the item can not occur until after the erection of the block in which it will be placed has been completed. Likewise, the phrase *During Block Assembly* indicates that the item will be landed or joined with the block during the block's assembly phase; it represents on-block outfitting. Not shown in this Table, and therefore not tracked by the project model, are the first two stages of assembly as identified by ZOFM. Theses stages, *On Unit Outfitting or Unit Assembly* and *Grand Unit or Grand-Unit Joining*, are associated with the process of joining a component to another component which will eventually be landed either in a block or on-board the ship. An example of this is a controller for a fire pump module; it is joined, with some other equipment, to a firepump, but not directly to the block or the ship. It is the module that is actually joined, and therefore it is the module and its associated manufacturing processes that are tracked by a ship construction program's upper management.

Equipment	Associated Block	Ship Construction Landing Phase
Main Engine	3102	After Block Erection
Reduction Gear	3102	After Block Erection
Main Engine	3402	After Block Erection
Reduction Gear	3402	After Block Erection
SSDG	2201	After Block Erection
SSDG	2202	After Block Erection
SSDG	3202	After Block Erection
SSDG	3501	After Block Erection
SSDG	3502	After Block Erection
Switch Board	2221	After Block Erection
Switch Board	2222	After Block Erection
(2) Switch Boards	3221	After Block Erection
Switch Board	3521	After Block Erection
Switch Board	3522	After Block Erection
Steering Gear	4421	During Block Assembly
Steering Gear	4422	During Block Assembly

Table XV. Equipment Landing and Associated Ship Manufacturing Level

Identification Of Event Interdependencies Or Linkages. In addition to identifying the events that will be tracked, the dependencies or linkages between them also need to be identified in order to develop a model that accurately portrays the shipbuilding process. These dependencies and linkages cover a wide range of focus that includes both the general sequencing of the events, and the delays inherent in progressing from one event to the next.

For this project, the linkages between each event were modeled as closely as possible to the actual linkages that occur in a shipyard. A simple example of this is some of the dependencies that were developed for the outfitting process. As already mentioned, the outfitting process is represented in the project's product**, Virtual Ship Production**, as three simple and basic events: Equipment Ordering, Equipment RIP, and Equipment Landing. The dependencies that were developed to help realistically portray this sequence are listed below.

- Equipment ordering occurs prior to equipment RIP.
- Equipment RIP occurs prior to equipment landing.
- Equipment landing can not occur until after the appropriate block is ready to receive it (i.e. depending on the equipment either after block erection or during block assembly).
- There is a one day delay imposed prior to the start of the next sequential event (i.e. if RIP for a specific equipment concludes on Monday, the landing of that equipment can not start until Tuesday).
- The baseline timespan between ordering equipment and receiving is commensurate with the procurement lead time required for ordering that equipment.
- A crane is required to be available in order to transport the equipment from the equipment staging area to the area in which it will be landed.

- Construction of the block is not completed until all components are installed.
- If the equipment is to be installed on board then it will be landed prior to the block's covering (i.e. through open air).

Similar dependencies were also created and imposed on the ship's structural construction processes as identified by the project's product model, **Virtual Ship Production** (i.e. Block Fabrication, Block Assembly, and Block Erection).

In addition to these dependencies, inter-block dependencies, or linkages, were also developed for the erection sequence in order to ensure that any proposed Hull Erection Schedule accurately portrayed and incorporated the sequencing prerequisites that shipyards are subjected to. These inter-block dependencies are identified in the following list, and are applicable to the majority of blocks associated with a ship.

- Erect from the mid-body area outwards.
- Inner blocks are erected prior to wing wall blocks.
- Blocks are not covered until all appropriate equipment that needs to be joined to them at the erection site are landed (for this project see Table XVI).
- Erection of a block on top of another requires that the lower block, and adjacent lower blocks within the same 'Unit' are already erected.
- Sufficient time is provided for the fitting and welding of blocks prior to landing new blocks over them.

In short, the above mentioned dependencies are rules that in most cases closely resemble the 'rules of thumb' utilized by shipyard planners. How close these 'rules of thumb' are adhered to is dependent on the specific design aspects of the ship being erected. For this project, these rules form the cornerstone around which any proposed erection schedule will be built. As such, they have been entered, where applicable, as predecessors to each event in the ship's production schedule, and should not be over-ridden except by the program manager, or his or her representative, in order to ensure model integrity.

Software Product Interface

The next few subsections describe the user interface of the **Virtual Ship Production** product, and some of the interface's special features. These special features include the ability to apply cost figures to the tasks being tracked, as well as being able to apply both the Ship Work Breakdown Structure (SWBS) and Product Work Breakdown Structure (PWBS) classification system to them.

Data Entry Templates. The main, or first, template of the **Virtual Ship Production** product is shown in Figure 3. The discussion and screen prints that follow this figure describe the user interface, or templates, of the product **Virtual Ship Production**.

Clicking on the Data Tool button, Figure 4, will bring up the Virtual Data form. This form is used to view and edit data that is specific to the ship building schedule. The data that is available on the Virtual Data form is more detailed than that which is generally available in the project schedule file. Any schedule data that is edited on this form is transferred back to the project schedule file thereby changing it. Any non-schedule data that is added or edited will also be stored with the project schedule file.

The Virtual Data form, Figure 5, is comprised of two main areas. The filter area allows the user to narrow the scope of task events that can be viewed. The tabbed folder displays the actual project data.

The filter area has three option buttons and a drop down list. The option buttons determine what type of task events to show in the drop down list. One can

Figure 3. Virtual Ship Production Master Template

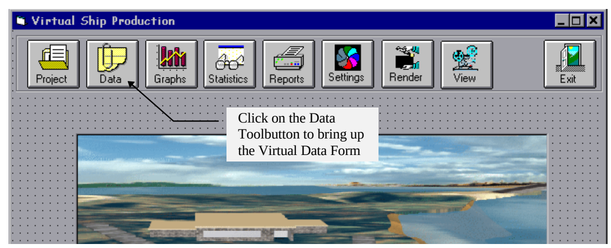

Figure 4. VSP Data Tool Button

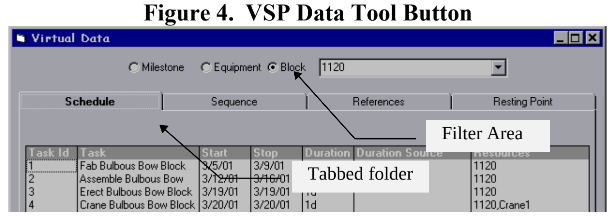

Figure 5. VSP Virtual Data Form

select either milestone, equipment, or block tasks to be listed on the drop down list. From the drop down list a particular item can be picked and the data viewed on the tab folder.

The tabbed folder has four tabs across the top that break out the details of the project data. These tabs are titled Schedule, Sequence, References, and Resting Point.

The Schedule tab, Figure 6, contains a table grid that displays some of the basic data items from the project. The table grid is divided into seven columns. Each column has a self

explanatory heading identifying the type of data contained within it. The seven column headings are:

- Task ID
- Task
- Start
- Stop
- Duration
- Duration Source
- Resources

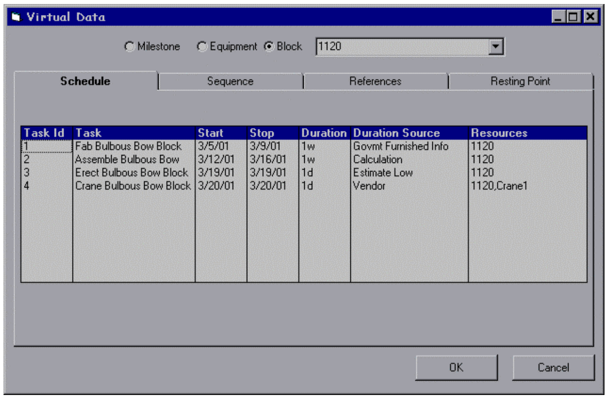

Figure 6. VSP Schedule Tab

The Sequence tab, Figure 7, displays the data relevant to the task's position or sequence within the project schedule. Included on this tab are columns that display the task's predecessor and successor information. A column for miscellaneous information is also included.

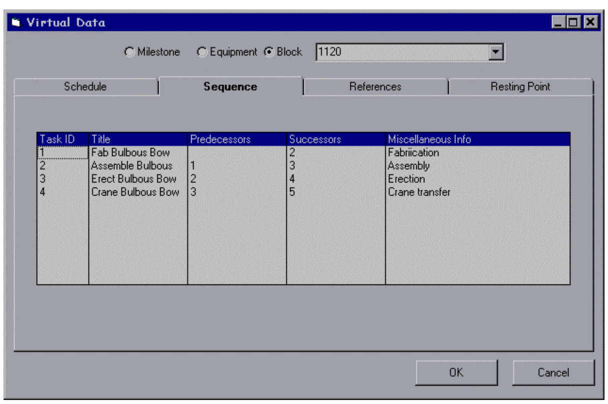

Figure 7. VSP Sequence Tab

The Reference tab, Figure 8, lists the tasks related to the filter selection and any background or referral information. The columns of data displayed are:

- Task
- POC (Point Of Contact)
- Phone
- Task ID
- Cost
- PWBS (Product Work Breakdown Structure)
- SWBS (Ship Work Breakdown Structure)

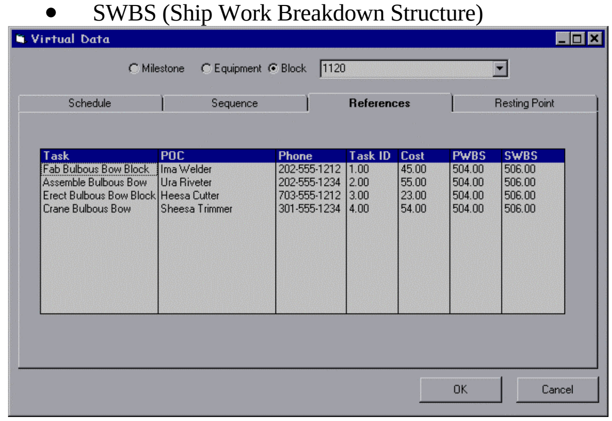

Figure 8. VSP Reference Tab

The Resting Point tab, Figure 9, provides both a visual and coordinate display of where the ship's blocks will be landed at the erection site. The resting points can be shown by individual block or by a group of blocks. For an individual block, the Filter section above the tabbed folder can be used to select the block of interest. The type of groups can be selected either by zone or for the entire ship. The display of zone resting points is done by clicking the mouse over a particular zone. All resting points and their coordinates relating to that zone will then be shown on the list box.

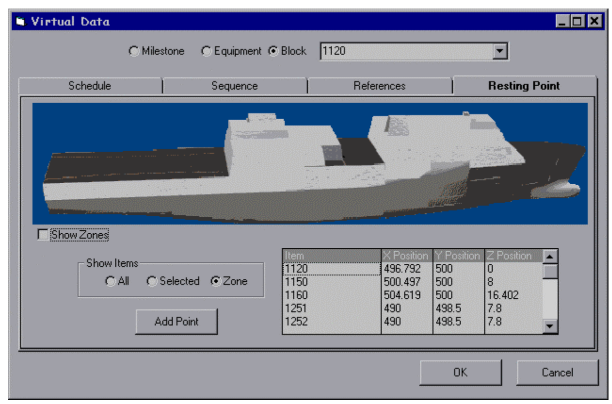

Figure 9. VSP Resting Point Tab

If the user is not familiar with the applicable zones, the Show Zones check box, Figure 10, can be clicked and the zones will be overlaid on the ship diagram. The XYZ position of the item's resting point can be edited as required. Clicking the Add Point button will create a new resting point for the user to enter the appropriate coordinates for.

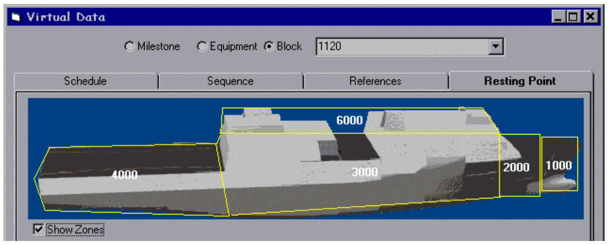

Figure 10. Show Zones Check Box

The **Virtual Ship Production** product also provides controls that allow the user, or VSP system administrator, to change some of the low level settings that affect the look and feel of the visual rendering. The controls for these settings are accessed by clicking on the Settings tool button on the Main Form, Figure 11. Doing so brings up the Setting Central form.

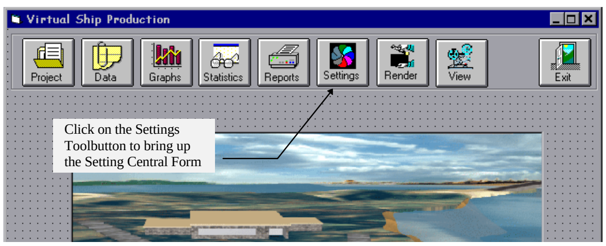

Figure 11. VSP Settings Tool Button

The Setting Central form is a tabbed form that segregates the different classes of data. The tabs are Areas, Queue, Week and Deltas.

The Areas tab allows the administrator to modify or add staging areas. Editing is done in typical word processing fashion by highlighting the value to be changed and using cursor keys to delete or change the entry. Adding a value is done by moving the cursor to a blank row and typing in the values.

The Queue tab is very much like the Areas tab in that it displays the names and coordinates of the queue positions. Editing and adding values for the queues is also done in the same manner as the Areas tab.

The Week tab allows the administrator to alter the positions and set the timing of the 'week buttons.' The following data entry points are provided for each position (i.e. in and out): X position, Y position, Z position, and Timing.

The Deltas tab is where the system administrator is able to fine tune the rendering process of the **Virtual Ship Production** system. The five sub-areas are:

- Hoist Point
- Time Deltas
- Miscellaneous Deltas
- Hide Point
- Abbreviate Milestones

The Hoist Point sub-area is where the coordinates of the crane hoist point is set. In addition to the X-Y-Z values, the timing or duration of the hoist event is entered in this sub-area.

The Time Deltas area is where the delay frame values for the following events are entered: leave, elevate, center point, final, reschedule. These events are described in Table XVI.

Event	Description
Leave	The number of days a block or piece of equipment is delayed before being elevated out of the staging area.
Elevate	The difference between 'elevate' and 'leave' is the time (in days) required for a block or piece of equipment to move from the staging area to the elevate point.
Center Point	The difference between 'center point' and 'elevate' is the time (in days) required for a block or piece of equipment to move from the elevate point to the center point.
Final	The difference between 'final' and 'center point' is the time (in days) required for a block or piece of equipment to move from the center point to its final resting point at the erection site (or, for certain equipment, the assembly building).
Reschedule	The minimum number of days the schedule for lifting a block or piece of equipment from the staging area is delayed due to a scheduling conflict.

Table XVI. Time Delta Events

The Miscellaneous deltas apply to other various functions in the rendering process. They are identified in Table XVII.

Function	Description
Milestone Time	The duration, in frames, of a milestone show event.
Elevate Height	The height in coordinate values to elevate an item above the staging area.
Hour/Frame	The number of hours per frame represented by the rendering.
Frame Default	The number of frames used if no other delta applies.
Reserved	Open for future enhancements.

Table XVII. Miscellaneous Deltas

The Hide Point sub area is where the coordinates for the hide point are entered. The Hide point is where blocks or pieces of equipment are pre-staged out of view in the rendering, just before they are moved to a staging area. The timing text box is where the time value or delay, by frame, for pre-staging is set.

The Abbreviate Milestones check box is used to set whether a fixed period of time is used for milestones or whether their actual time of duration is used. This feature is generally used when there are numerous milestones that precede any building activity. When checked, the milestones will be shown at fixed periods, according to the milestone timing set, instead of their relative time and thus shortening the inactive period of the rendering (i.e. the period during which construction activities are not visually being displayed).

Element Classification And Cost Entry Data Points. In order to accommodate the functionality offered by the Product Work Breakdown Structure (PWBS) and Ship Work Breakdown Structure (SWBS) classification system, as well as the potential linkage of data between this project's product and the Product Oriented Design and Construction (PODAC) Cost Estimating Model currently under development, a PWBS, SWBS and cost data entry point for each event tracked by the product model is included in the 'Virtual Data - References' template. The direct importance on the project's product of these entry points is that they provide the ability to track costs by their associated products and events in a time or calendar format. This will allow the user to create prospective expenditure schedules and graphs, as well as comparative (actual versus proposed) ones.

The exact code that will be used to identify each individual type of product in accordance with the PWBS breakdown structure is currently being developed under the Mid Term Sealift Ship Technology Development Program. The coding used for the SWBS data entry point, on the other hand, is in accordance with the current NAVSEA SWBS coding system.

Visualization Model

The shipyard depicted during the visualization process of the ship construction program is a generic shipyard that shows the minimum amount of information required to visually convey the merits of the viewed ship construction program. As such it contains one dry dock, twelve block staging areas, six equipment staging areas, a block queuing area, an equipment queuing area, and an assembly building. In addition to these items a stainless steel colored placard is located at the top of the screen over the shipyard. Upon this placard the ten milestones and miscellaneous events from the ship's Master Construction Schedule, as identified in the paragraph titled **Milestones/Miscellaneous**, are displayed as they occur. Each one is depicted as a raised, stainless steel colored button with black lettering.

The model's clock is also displayed on the placard in addition to the ten buttons. It is located at the bottom right hand corner and consists of two buttons; one labeled 'Week', and the other the appropriate numerical symbol (i.e. 1, 2, 3, etc.). Although visually the time is progressing by two hour intervals, the time units associated with an event can also be adjusted by the user through the **Virtual Ship Production** interface.

The block staging area contains a maximum of 12 lots that can be utilized by the ship production program. The exact number that will be used is dependent on the shipyard that is being modeled, and requires input by the user. Although the lots remain on the screen during the visualization process when they are not used, they are also not loaded with blocks. In this way they can be thought of as resources, for they are used only when available, and the actual number available does affect the outcome of the ship production program.

Associated with each staging area is a queue line, or area. These queues are included in the product model's visualization process in order to help convey the merits, or pitfalls, associated with the Master Construction Schedule being displayed. Along with the staging area lots, they can be used for visually determining if a production plan underutilized a shipyard's resources, or over utilizes them. If the latter is occurring then work in process (WIP) is also occurring. This is seen when the lots associated with the queuing area begin to be loaded with blocks, or equipment, waiting to arrive at the staging area. A good example would be when the schedule indicates that there are 16 blocks in the staging area. In this case, all twelve lots are being used, and there will also be four blocks shown in the queuing area. Under utilization of the shipyard resources, on the other hand, can be seen when the available lots in the staging areas are never fully utilized (i.e. there is always at least one lot that is empty). Another way to determine these characteristics of a construction plan is through the report option available in the project schedule and database software. Although not as visually appealing, reports using this option are able to deliver much more detailed information.

The assembly building is included in the visual display of the shipyard to show where some of the equipment might go after arriving in the shipyard. A good example of this is the steering gear. At the conclusion of the RIP process, as determined by the Master Construction Schedule, each gear is shown visually arriving in the equipment staging area and then traveling and disappearing into the assembly building. In this way they are visually shown as being joined to the block during its assembly phase instead of landed in the block after it has been erected.

The specific start/stop dates for the element moves (i.e. blocks and equipment) identified in the visualization sequence were determined by utilizing certain task start and stop dates as determined by the project schedule file. The specific tasks and date identifiers utilized are listed in Table XVIII.

Task or Event	**Date Identifier Utilized**	**Visualization Movement Relationship**
Block Assembly	Actual End Date	Arrival of the Block in the Block Staging Area
Block Erection	Actual Start Date	Departure of the Block from the Block Staging Area
Equipment RIP	Actual Start Date	Arrival of Equipment in the Equipment Staging Area
Equipment Landing	Actual Start Date	Departure of Equipment from the Equipment Staging Area

Table XVIII. Material Flow Determination Criteria

A snap shot of a demonstration run of the **Virtual Ship Production** product is shown in Figure 12. This snap shot is taken from a camera angle on the stern of the ship looking forward instead of the default position off the starboard side looking inboard. This change in camera position was made to demonstrate the flexibility of the visualization software's rendering process. By specifying the XYZ coordinates for the camera in the rendering process setup, the user can easily change the view of the ship construction process being displayed to suit particular needs.

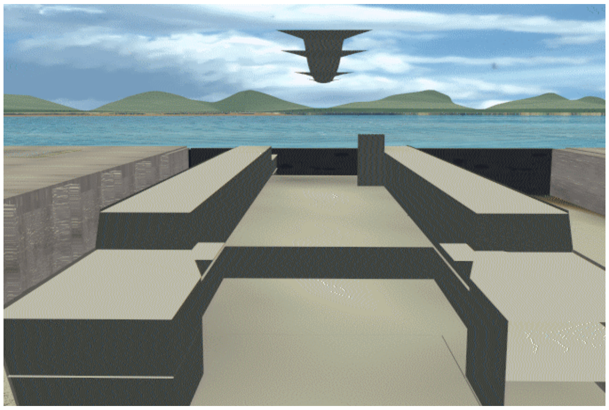

Figure 12. Stern View Of Ship Construction

Block Break Visualization. During the project, the visualization software was also used to view and print the graphical images of the equipment and individual blocks; the latter was also viewed by sub-zone in an exploded and unexploded format. This capability was found to be very useful in helping to verify the block break descriptions. Some samples of this capability are provided in Figures 13 and 14. Labels have been attached to the blocks in these figures in order to help identify them.

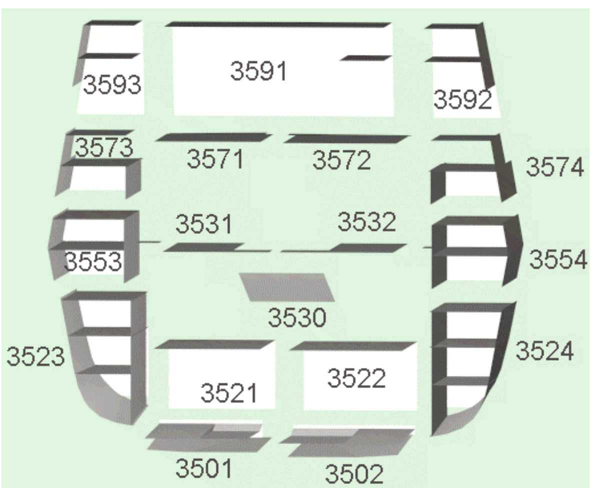

Figure 13. Exploded View Of Sub-Zone 3500

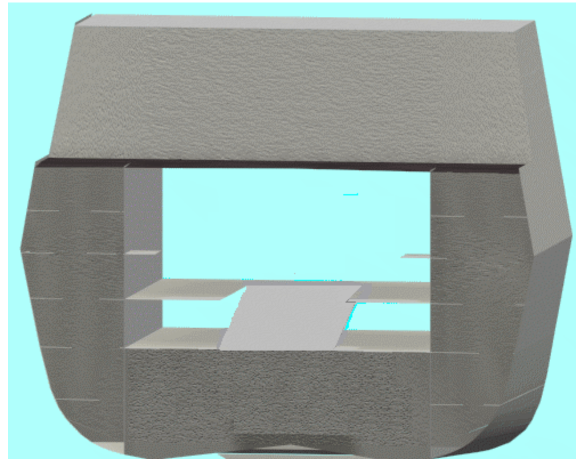

Figure 14. Solid View Of Sub-Zone 3500

Special Options

In order to provide user functionality to the **Virtual Ship Production** product a couple of special options were also created or designed into the product. These options include tools and/or capabilities in the following two areas: task filtering and risk assessment.

Task Filtering. An important feature of any scheduling or management tool is its ability to filter information as required or needed. This is especially true when managing large projects like ship construction, where many types, or groups of information are often placed together in a single schedule, report, or file.

In this project, the ship construction project file contains both task and resource related information. These two classes of information type can be further divided into numerous sub-classes each of which tracks a specific aspect of the applicable ship production program. In order to assist the program manager in the retrieval of this information, a number of filters were added to the default list provided by the project scheduling software. These additional filters were created by using the filter editing capabilities of the project scheduling software and entering the relevant information in the appropriate project file data columns. A brief description of each of these additional filters is provided in Table XIX.

Risk Assessment. Although schedules do aid in the organization and management process of any project, they are not necessarily accurate. Because the information entered into a schedule is only as accurate as its source is able to make it, the information received from a schedule is rarely if ever one hundred percent accurate. This is especially true for the dates and durations of the events being tracked within a schedule. Quite often these factors are guesses and estimates based on past performance, or the actual past performances of similar processes. They are not guaranteed. In light of this, the capability of creating schedules based on statistical distributions is highly desired. When this is done, and a number of iterations are accomplished, a risk assessment of the schedule is performed. The result is a compilation of schedules ranging from the most probable to the least probable, and a number of possible critical paths.

In order to allow the user to be able to add this functionality to his or her management project, **Virtual Ship Production** has been organized in a manner that allows the incorporation of a couple of different risk analysis systems. These systems provide project management functionality that allows the user to assign statistical distributions to selected task events and event duration. With this capability the user is able to perform a number of iterations on the schedule in question, and determine the most to least likely schedule scenarios, project duration, critical paths, and critical path tasks.

Filter Name	Filter Description
Block	Show all tasks associated with the specified block number.
Filter Out Process/Stage	Show all tasks that are not associated with the specified process or stage.
Process/Stage and Block	Show the task that contains this specified process or stage for the identified block number.
Process/Stage & Zonal/Unit Range	Show the tasks that contain this specified process or stage for the identified range of zones or units.
Process/Stage	Show all tasks associated with the specified process/stage.
Zonal/Unit Range	Show all tasks associated with the specified range of zones or units.

Table XIX. Filters

Resource Load Leveling

In addition to the above mentioned special options, the project scheduling software also offers three methods of determining project durations. These methods are fixed-duration scheduling, resource-driven scheduling, and a combination of the two. Fixed-duration scheduling is strictly time based using task durations that are interlinked with the scheduled task start and stop dates. In resource-driven scheduling, however, the task durations are based on the work content of the task and the amount of resources assigned to it. When a combination of these methods is used some of the task durations are determined by one method, while the remaining task durations are determined by the other method.

As indicated above, the application of resource-driven scheduling allows a project schedule to be tailored to fit the actual resources available for performing the assigned tasks. This capability of the project scheduling software lends itself well to the scheduling and analysis features of the **Virtual Ship Production** product. Through the application of resource-driven scheduling, ship production schedules can be analyzed with regards to the specific capabilities of a shipyard. When resources are applied to tasks at a degree greater than their capacity, however, resource load leveling conflicts occur. Fortunately, the project scheduling software is able to identify when this happens, and immediately notifies the user. The user, or project manager can then manually, or with the assistance of the options provided within the project scheduling software, resolve the conflict by leveling the resources, and thereby adjusting the schedule.

In using the **Virtual Ship Production** product it is recommended that at a minimum resource-driven scheduling be applied to the crane transfer tasks. The utilization of this capability on this event will not only help to identify where resource load leveling conflicts occur, but also as a minimum produce a schedule that is representative of a shipyard's crane capacity for landing blocks and equipment at the erection site.

Visualization Technology Conclusions

The visualization process developed for the **Virtual Ship Production** product is a tool that can be used by all levels of the shipyard management team and program acquisition team. The Ship Acquisition Program Manager (SHAPM) can use this tool to manage the project, to monitor progress, evaluate construction scenarios and generally keep Integrated Product and Process Development (IPPD) teams completely abreast of the latest construction process as the ship acquisition process takes place. This schedule/visualization tool is also useful for high level presentations at NAVSEA or command level briefings.

Other specific areas in which computer visualization can be used as a tool in shipbuilding include:

- Linkages to shipyard detail schedules:
  - **(a)** Engineering plan schedule
  - **(b)** Outfitting
    - Pallet schedule
    - Long Lead Time Material (LLTM) schedule
    - Shop schedules - Marshaling yard
  - **(c)** Hull steel unit schedules
    - Shop
    - Platen
    - Gate/work station
  - **(d)** Erection schedule
    - Grand units/Blocks
    - Shipway
  - **(e)** Zones - on ship
    - Zone outfitting schedules
- Present new production sequences to show rescheduling influences
- Progress tracking with color presentations for shipyard internal use
- Training tool for production planners, superintendents and foremen
- Process lane resource planning, and throughput/bottle neck identification
- Training tool that provides an animated demonstration of the erection sequence
- Progress presentations, and expected progress presentations, for government Quarterly Progress Reviews (QPR's)
- Internal management presentations to do "what ifs" at the vice president level and higher
- Detail tracking of completion at the work station or gate level with process lane/work station simulations
- Gate presentation for supervision showing the manner in which the unit will be sitting for welding and for outfitting in their gates

CONCLUSIONS

Many conclusions can be drawn from the previous sections. The basic premise of these conclusions though should be that if utilized properly, simulation based design, and visualization technology, offer an extremely high return on investment. With a very wide scope of application, from the production planning function and the planning efforts through to the vice presidential level for high level presentations, these two technologies are an aid to all levels of the shipyard management team.

A specific area in which these techniques would be helpful to a shipyard is in the development of their build strategy. This is because the build strategy includes within it a sequence of erection which in turn influences all of the upstream production department involvement and scheduling decisions. A ship's build strategy and resultant sequence of erection therefore are strongly influenced by the various aspects of the shipyard environment. These aspects include the building and erection site availability, as well as material availability, and concerns in the level loading of human resources and cash flow. It is with these problems and concerns in mind, that visualization and the benefits of computer simulation aides are considered most helpful in the planning process.

As indicated, both simulation based design and process flow simulation are wonderful tools for design and analysis purposes. When utilized properly they offer the opportunity to analyze design decisions for bottlenecks and inefficiencies early in the design cycle where changes and modifications can still be made. This capability allows the design team to produce an optimized, or highly efficient design, with a high degree of confidence. Another benefit of these design techniques is that when a design is selected for use its performance characteristics will be known. Modifications or improvements to existing designs can also be analyzed for their effectiveness through the application of process flow analysis. The only drawback with this technique of design and analysis is that its results are only as accurate as the data used to develop the simulation model.

Unfortunately, if these processes are applied late in the design process, such as near the completion of the contract design stage, the implementation of any modifications to the design based on the results of these studies is remote. Any and all suggested modifications to the design would have to be carefully evaluated; weighing the benefits of the modification(s) against the cost impact of implementing them. Because of this, it is recommended that in all future ship design programs process flow design and analysis methods be applied as early as possible in the ship design process in order to obtain the maximum benefits offered by this technique.

ACKNOWLEDGMENT

This paper is based upon work performed for the US Navy's Affordability Through Commonality (ATC) Program operated under the Naval Sea Systems Command (NAVSEA). ATC's objective is to reduce the total life cycle cost of ownership of Navy ships through increased equipment standardization, the use of common modules with standard module interfaces, and process simplification including modular ship architectures with zonal distributed systems and a generic production oriented build strategy.

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Shipyard Technology Development Strategies

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ABSTRACT

Effective development strategies for shipyards need to recognize the different economic and technological environments in which individual organizations operate. The benefits of implementing a given technology will vary according to the different cost structure, labor market and technological development of the individual shipyard. Specifically, capital investments in expensive hardware, can lead to a deterioration of the overall performance of the business, whereas improvement in the organization and practices of the business may produce improved performance from the existing hardware and facilities. Development strategies must be targeted towards quantifiable improvements against the needs of the market or competition and must recognize the impact of different technologies on the performance of the particular yard. This paper looks at the issues involved and appraisal techniques to support effective investment in hard and soft technological developments

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NOMENCLATURE

AWES Association of West European Shipbuilders
CGT Compensated Gross Ton
EY Employee Year
GT Gross Ton
JSA Japanese Shipbuilding Association
UK United Kingdom
US United States of America

INTRODUCTION

The intrinsic mobility of ships forces shipyards to compete for their customers in an international market place. It matters little to the purchaser whether the vessel ordered is built in Northern Europe, the Americas, or the Far East, provided that the stipulated price, delivery, reliability and operational objectives are met. The diversity of economies in which shipyards operate, however, ensures that there are substantial differences in many aspects of their operating characteristics. The global nature of the market, therefore, results in a composition in which not only are the adversaries of contrasting statures, but are playing on a field that is far from flat. Thus the adoption of the correct strategy for a yard is critical to obtain an effective use of investment funds and the right balance between hard and soft technology to achieve a competitive cost per unit output.

Development is a means of transition from one state at some point in time through to some future state. The potential pace of development is related to the development and adoption of technology in general.

Shipyards use elements of the available technology and adopt them to improve productivity and ultimately performance [1].

The level of technology adopted at any time depends on the following:

- the technology available,
- the technology approved for use, and
- the cost structure of the yard.

That is, as labor rates increase and the cost per unit output increases then investment in technology could be justified on a Return on Investment basis. Typically for a shipyard the payback period is dependent on the time scale of the present order book and the number of workers displaced by the technology implementation. Consequently, different shipyards with different cost structures can justify the adoption of different technologies at different times (see Figure 1). As available technology is approved for shipyard use then those yards that have a high labor cost base tend to adopt it sooner. Yards with a lower labor cost base will lag behind creating a technology gap.

A good example of this is laser welding. The technology to undertake laser welding has been developed over the last 10 to 15 years [2], whereas approval by classification societies its the limited use is only now becoming available. The higher labor cost yards are looking for rapid adoption because of the reduction in distortion it offers which is fairly labor intensive to remove.

The most efficient yards tend to make these decisions with the aim of obtaining a cost advantage rather than a technology lead. Other yards adopt a strategy whereby closing the technology gap tends to dominate the strategy often leaving the yards as low labor cost but high unit cost facilities.

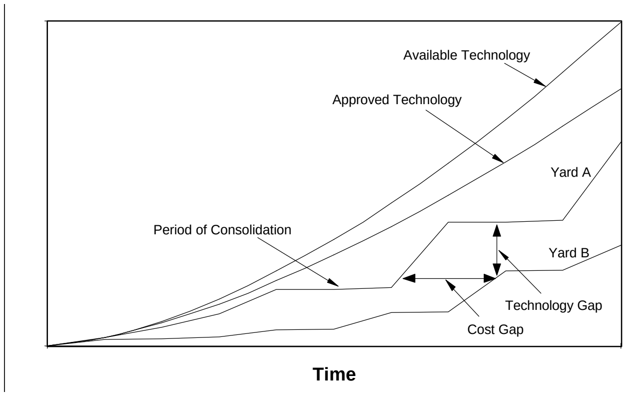

Figure 1 Patterns of Shipyard development in relation to available technology

Clearly, as labor costs increase through development of the local economy, there will be opportunities to justify a transition from one level of technology to another, where the periods between developments are periods of consolidation.

Technology itself has two aspects the hard and the soft aspects. Hard technology refers to the physical tools and equipment (hardware) required to design and build ships in a shipyard such as welding equipment, robots, CAD-CAM, etc. Soft technology refers to the management, organization and procedures that are in place to maximize the use of existing facilities and human resources, procedures, processes and systems for functions such as planning, quality control, cost control, material control, education and training, etc.

A technology development strategy for a shipyard must therefore consider its current level of competitiveness and the present performance of its hard and soft technologies. If the performance of the soft aspects is good then the maximum benefit is being obtained from the existing facilities and further prudent hardware investment would tend to reduce cost per unit output. However if performance of the systems and management processes is inadequate then there is a temptation to ‘buy the shipyard out of trouble’ by investing in ever more up to date hardware, but this tends to actually increase the cost per unit output.

In order to identify useful development strategies for a given yard, it is necessary to establish its competitive position. This task is complicated by the global context of the industry and the resulting variety of shipbuilding enterprises, but benchmarking procedures have been developed [3] which enable the effectiveness of the work processes of a given yard to be compared with that of others. In particular benchmarking allows the discrepancy between an individual yard's position and that of the worlds best to be identified. Individual yards can also be evaluated in a second way, by undertaking a technology audit. This quantifies the level of technology employed by the yard, and is therefore an important indicator of its performance capability. In the first part of this paper both these established tools are outlined, while in the body of the paper the application of these concepts is discussed. This is shown to provide insights into the relevance of alternative development strategies that could be adopted by individual yards in order to improve their position in the international market for ships.

COMPETITIVE BENCHMARKING

Benchmarking requires an agreed measure which can be evaluated for every company in order to compare an individual company's performance with that of the company which is recognizably the best. The general approach now in use by the industry consists of two elements to measure:

- **cost competitiveness** - a measure of cost per unit output, and
- **technological sophistication** - a measure of the aggregate level of hard and soft technology adopted.

These measures allow shipbuilders to compare their current performance with that of competitors and to set targets to be achieved as part of the strategic objectives for the business. These two measures have become the shipbuilding industry standard for comparison and thus can provide a basis upon which individual yards can base a development strategy to underpin the achievement of strategic performance targets.

Cost competitiveness

In the commercially competitive world of shipbuilding a measure of cost per unit output indicates a company's effectiveness [4]. This approach is now well established since its first use by Appledore International [5] and has been used for a number of studies. A summary is provided here for completeness.

Using the calculated costs and output a simple, but effective, comparison of the performance of different yards can be made in terms of cost per unit of output. In calculating the cost and output for a given yard it is advisable to collect data over an extended period of perhaps three years, in order to average out the effects of work in progress. As the benchmark comparisons are intended to be internationally applicable the costs are calculated in US dollars (although exchange rate movements should be borne in mind as they make an analysis time dependent).

Costs As benchmarking is concerned with the effectiveness of the company's procedures (i.e. in adding value to the raw material inputs), the costs should exclude those for the direct materials attributed to specific contracts and concentrate on the added value (i.e. the remainder making up the total operating costs for the company). This is calculated by summing the following totals:

- wages paid to all employees, including overtime and bonuses,
- costs for all subcontractors,
- social costs of employing workers,
- costs of materials and services to run the business (not chargeable to specific contracts),
- overhead costs, and

- cost of supply-and-fit type subcontracted items.

Output Shipyards produce a wide range of vessels which vary both in size and in complexity of construction. The traditional measure of output has been the steel weight of the vessels produced, but this does not take account of the higher work content necessary for vessels which are more complex to build. Other measures of output, such as total deadweight, or total Gross Tonnage (GT) are no better in this respect. Collaboration between the Association of West European Shipbuilders (AWES) and the Japanese Shipbuilding Association (JSA) resulted in the Compensated Gross Ton (CGT) as an international measure of output [6]. For any ship this is established by multiplying the GT by a coefficient which reflects the amount of work necessary to produce that particular type and size of ship. The latest figures used for the CGT coefficients were produced jointly by the Organization for Economic Co-operation and Development, AWES and JSA [7].

Cost curves Performance presented simply as $ per CGT however fails to indicate the qualitative difference between shipyards operating in high or low wage economies. For a given shipyard, the wage levels are predominantly an external factor beyond the control of the business and as such represent a constraint rather than a controllable variable.

This issue can be addressed if the measure is dis-aggregated into two component elements, and data collected accordingly, namely:

- cost per employee year, and
- employee years per CGT.

Clearly the product of these two functions results in the same benchmark measure of cost in $ per CGT, but allows the information to be presented in a more revealing way, as shown in Figure 2. On this chart the vertical axis is employee years per CGT, the horizontal axis is cost in $ per employee year and the curves represent a series of iso-cost lines for a range of cost per unit of output values. Any given yard can be plotted as a discrete point on the chart and will lie on the cost curve representing it own performance. The bold line indicates the current international benchmark, which is a best performance of around $800 per CGT.

On Figure 2 two hypothetical shipyards are shown which are achieving this benchmark performance under different conditions. By presenting, the performance in this way it can be seen that yard A is a low cost and low productivity yard, while yard B is high cost and high productivity. Yard A is operating in a low wage economy with procedures which are labor intensive and use little automation, in contrast yard B is operating in a high wage economy where the more expensive labor costs would be offset by increased productivity. Yards which appear above this benchmark line, on cost curves representing higher cost per unit of output, are not operating competitively, and should look to improve their performance to become competitive. In improving their performance they will progressively move onto lower cost curves until they reach the benchmark value and then drive the benchmark lower as they become market leaders.

Initially this approach concentrated on the merchant shipbuilding sector covered by the CGT coefficients. However such techniques have now been successfully applied in naval shipbuilding [8].

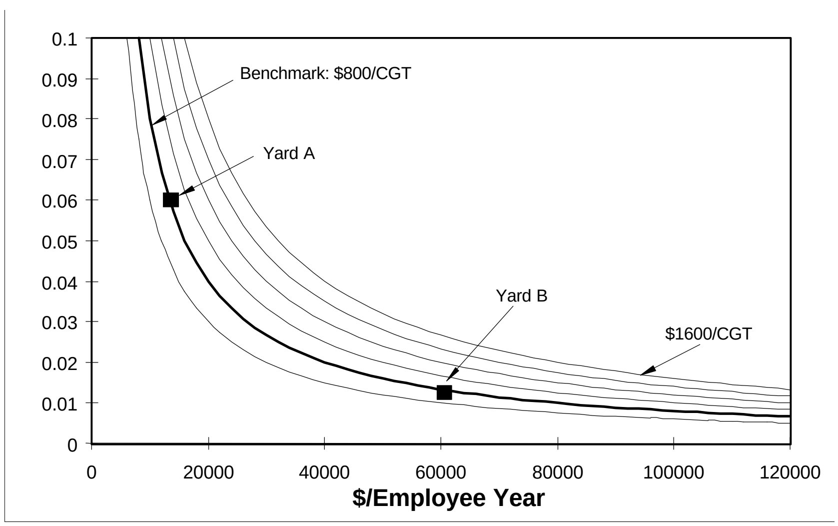

Figure 2 Global shipyard competitiveness presented on cost curves

Technological Sophistication

A comparison of the technological sophistication of shipbuilding yards can be undertaken through technology audits [9] thus evaluating the business through a different perspective. The audit does not assess the actual performance of a yard, but rather establishes the potential capability of a yard as a result of its investment in technology. The audit is undertaken by examining a series of specific elements in the shipbuilding procedure and rating these on a technology scale set from 1 to 5.

The full audit considers 72 basic elements, these being subdivided into 8 audit modules, covering both the hard (e.g. machinery and equipment) and soft (e.g. management and operational systems) aspects of technology. The resulting assessment of a yard's technological position can then be presented as a technology profile in the form of a bar chart. This can be done for the individual audit modules, or for the weighted average value of all the audit modules to show the position of the yard as a whole.

The five technology levels used in the audit reflect the state of technological development of the most advanced yards over the past 30 years.

- **Level 1** is that of shipyard practices in the 60s, with several berths serviced by small cranes. There is little mechanization, and outfitting is largely carried out on board ship after launch.

- **Level 2** reflects best practice of the early 70s, with fewer docks, larger cranes, and some mechanization. Computers are used for some operating systems.

- **Level 3** is the stage first achieved in the late 70s in new or fully redeveloped shipyards in the US, Europe, and Japan. A single dock is serviced by large cranes with some environmental protection. There is a large degree of mechanization and the use of computers.

- **Level 4** is the technology of the late 80s with a single well protected dock, with fully developed operating systems and extensive early outfitting.

- **Level 5** is the current state of the art with automation in some areas, and extensively integrated operating systems using CAD/CAM. It is characterized by efficient computer aided materials control and effective quality systems.

These five levels of technology are used to describe an entire yard, but similar descriptors have been established for each of the audit modules, and for the basic elements in each module.

In interpreting the audit results, it should be recognized that higher levels of technology are not intrinsically better, as high technology implies high capital cost which may be inappropriate in a low wage economy. It is widely recognized however that an even level of technology is important, so efforts should be made to avoid having elements of high technology which are isolated in an environment of lower technology. Development strategies based on the technology audit will seek to raise those elements of the technology profile which are falling behind a yard's overall level, and then to raise the overall level in a uniform way.

EFFECTIVE TECHNOLOGICAL DEVELOPMENT

The benchmarking tools described above provide managers with two perspectives on the business through which to establish the extent and direction of the development strategy appropriate to their business. The cost curve approach provides suitable targets for an improvement strategy based on a comparison between the performance of different yards, while the technology audit exercise identifies what technology investment options exist and where such investment should be targeted.

In a commercial environment, an effective strategy seeks to reduce the cost per unit of output relevant to the market sector in which a company wishes to operate to a level which:

- is lower than the current market revenue level; and
- establishes market leadership.

Technology is a means to achieving this rather than an end in its own right however this seems to have been overlooked by yards when initiating development programs. This has resulted in inappropriate investment in technology and/or ineffective implementation of the technology. To make matters worse, decision making processes are often distorted by conventional accounting practices, and too often a financial accounting perspective provides an inadequate or even misleading basis on which to evaluate potential developments. The key to avoiding this is improved understanding of the business, what the measures mean, and the effect of alternative strategies.

The following part of this paper looks at techniques that build on the two basic benchmarking tools. With a greater understanding of the component elements and clear differentiation between constraints and controllable variables, the relevant aspects in developing improvement programs and capital expenditure decisions can be identified

PERFORMANCE GRADIENTS AND BREAK-EVEN THRESHOLDS

Building on the cost curve concept, it is possible, however, to return to the chart to consider in more detail the probable impact of any proposed investment, and to determine the effect that this will have on shipyards with different current operating characteristics.

Performance Gradient

For a given yard, an analysis of the expected changes in operating costs and productivity, resulting from a proposed development, allows a second discrete point to be plotted on the cost curves indicating the new performance of the business following implementation of the technology. By joining these two points a gradient indicating which direction the yard's

performance will move on the chart is achieved as shown in Figure 3.

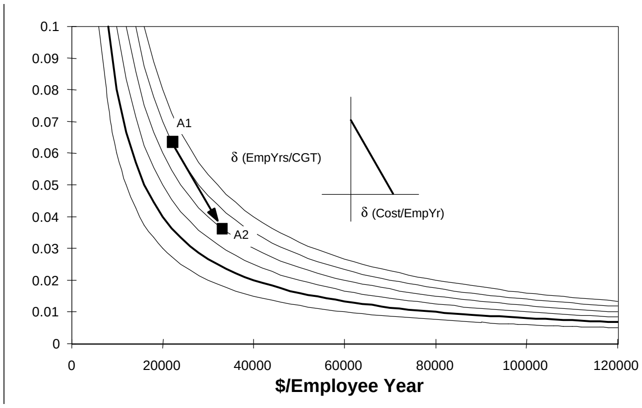

Figure 3 The performance gradient

To understand the relevance of this gradient to decision planning, it is necessary to understand what it represents. For any given technology investment, e.g. the automation of a process, the productivity per employee should be increased, but the costs per employee will also be higher as there will be increased overhead costs and a reduction in the number of employees. The increased productivity is calculated in terms of the reduction in employee years per CGT, and the increase in costs is calculated in terms of the net increase in costs per employee year. These are the two elements of the gradient shown in Figure 3. This 'performance gradient' can be calculated for the investment by dividing the expected change in employee years per CGT by the expected change in costs per employee year. Expressed mathematically:

$$\textbf{Performance Gradient} = \frac{\delta(\mathbf{EY/CGT})}{\delta(\mathbf{Cost/EY})} \quad (1)$$

Break-even Threshold

When a calculated performance gradient is plotted on the chart, it may either indicate that overall cost competitiveness of a shipyard will improve, as indicated for yard B in Figure 4, or that the performance will deteriorate, as for yard A. These two yards are shown as operating on the same cost curve, and so there must be a point between yards A and B at which the investment ceases to be detrimental, and becomes profitable. This is when the gradient line is tangential to the cost curve, and this point is called the break-even threshold for investment in yard C.

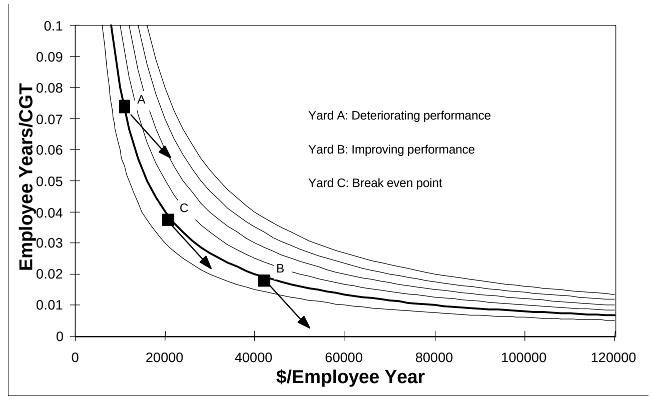

Figure 4 The breakeven threshold

Thus, the introduction of new technology that improves productivity does not guarantee that the overall performance of the yard will be improved. The illustration in Figure 5 shows the effect of different performance improvement gradients to different yards. In the case of Yard A, the gradient for Option 1 moves the shipyard onto lower cost curves representing improved performance (i.e. lower $ per CGT). However, the performance gradient for Option 2 is such that the yard moves in the wrong direction and there is a net increase in the $/CGT costs (i.e. its new position would be on a higher cost curve than it was prior to the investment). The situation is different, however, for Yard B when both options move the yard in the right direction representing improved performance.

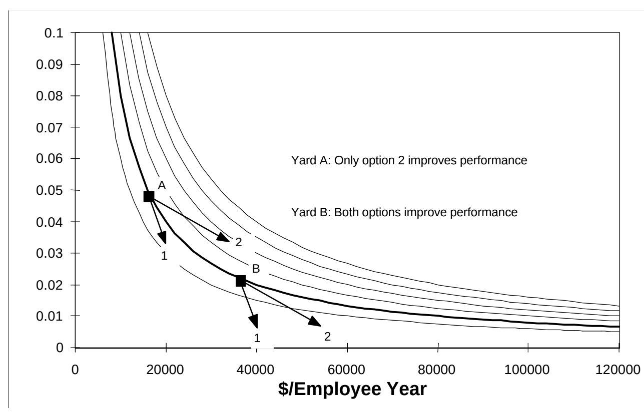

Figure 5 The impact of new technology on performance

For any yard therefore, the break-even threshold can be established for its current position on the cost curves, expressed in terms of the gradient of the tangent to the cost curve. Figure 6 shows a series of radial lines overlaid on the cost curves denoting the gradient of the break-even threshold for different points on the cost curves. Using these lines the break-even threshold for any yard can be established by simple interpolation.

Figure 6 Determining the breakeven threshold

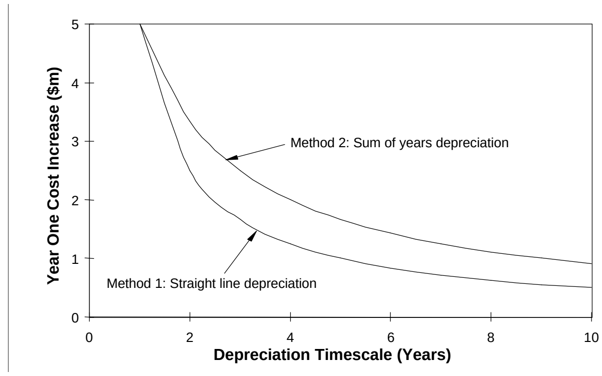

Figure 7 The impact of alternative depreciation methods

TECHNOLOGY COST ACCOUNTING

The technology audit reflects the result of investment in technology by a specific shipyard, associated with which is an investment cost. The investment cost in itself drives up the cost base of the shipyard and hence the cost per employee year parameter (X axis) of the output cost on the cost curves. To justify investment, these increased costs must be exceeded by the associated savings from the implementation of the technology - predominantly the reduced labor costs resulting from improved productivity.

The assessment of technology investment costs, both new and existing, is however often influenced by the traditional financial accounting treatments. In the case of investment in hardware, these costs are often capitalized and are reflected on the profit and loss account through depreciation provisions, thus diluting the impact on annual overheads in accordance with the depreciation term and method adopted. These choices are generally determined by the applicable taxation laws rather than an assessment of the economic life and benefit profile of the technology concerned. Given the major costs of many hardware investments, such as panel lines, paint cells and robotics, the choice between 5 or 10 year depreciation terms, and straight line versus sum-of-the-years depreciation method, can totally alter the economic appraisal as shown in Figure 7.

This phenomenon, along with the 'feel good factor' associated with the shiny new equipment and facilities of hardware investment, have combined to favor hard rather than soft technology options and probably lie behind much of the past sub-optimum investment in upgrading shipyard facilities. However, it is now generally accepted that much investment in hard technological solutions is less beneficial than soft technology options which may need, in any case, to be in place before the full benefits of some of the more advanced hard technology improvements can be realized. A yard registering a high score on the technology audit, whilst lying on a uncompetitively high cost curve, may well be reaping the misery of inappropriate investment in the past for which it will pay the penance of wearing an economic millstone for some time. In such instances the productivity hurdles for that business to operate competitively are higher than they might have been.

In understanding these potential distortions to the treatment of technology costs and in assessing the cost benefit profile and timescale of both hard and soft technological options based upon operational rather than accounting criteria, more effective deployment of investment funds can be achieved.

STRATEGY DEVELOPMENT

Competitive benchmarking may be used to assist a shipyard management team in establishing the target performance for the business and, used in conjunction with the other concepts discussed in this paper, to develop a program of initiatives to support the achievement of this.

Target performance

In developing a shipyard's improvement strategy, the measure of overall performance measured in $ per CGT becomes a very powerful tool to:

- establish the break-even rate to match the operating performance with market price levels,
- target the optimum market sector in terms of product mix and competitors,
- establish the performance improvement need for competitive operation,
- identify the impact of rising labor costs and throughput variations, or
- establish sensitivity to exchange rate variations against the dollar.

Target Marketing Once a shipyard has established its current position in terms of cost per unit of output measured as $ per CGT, basic viability (the first concern in any commercial environment) can be ascertained by considering this cost performance with the added value element (i.e. excluding direct material costs) of the market selling rate for its current product range. Using the 'Macawber' principle [10] if this rate is lower than the cost of production, the result is commercial 'misery'. In such circumstances either the business must improve its

performance to survive or must move into a sector of the market commanding a higher selling rate, and hence added value element, measured in terms of $ per CGT.

Figure 8 shows how the added value component for different ship types can be plotted against the current operating performance of the business. Where the market rate is above the line the shipyard can operate effectively. However, for those product types falling below the line, the business will incur losses. Overall profitability for an existing orderbook or planned product mix can then be determined based upon a weighted average (by value) and compared with the current operating performance.

Within a chosen market sector, a shipyard can compare its performance against its competitors in that

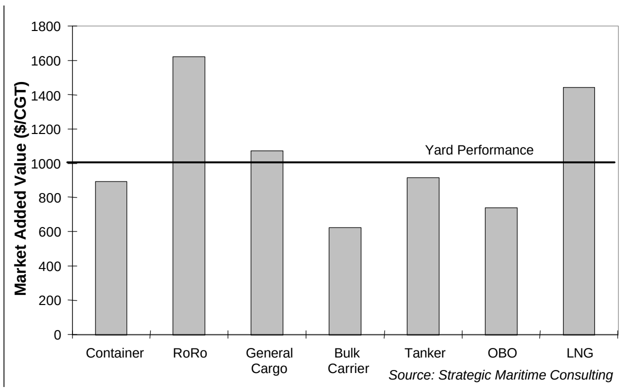

Figure 8 Target market identification

sector using the cost curves to assess not only the potential to improve profitability, but also, in the current position of supply side over capacity, the ability of the shipyard to win sufficient orders to effectively utilize its resources.

This approach has been developed and applied to establish an effective marketing strategy for individual yards [11]. It has also been used to assess the commercial viability and strategic implications of the transfer from naval to merchant shipbuilding considered by many US yards, and the effective market sectors for the higher cost Western European shipbuilders.

Throughput Volumes The volatility of world shipbuilding demand and the relatively high barriers to market entry and exit have produced a market with an elastic demand curve and a relatively inelastic supply curve. The resulting imbalance between supply and demand leads to periods of supply side overcapacity which have been exacerbated by capacity additions in certain areas of the world. The intense competition arising from this has not only driven prices down, it has also meant that many yards are finding it increasingly difficult to fully utilize their resources, either physical or human, and are looking at reduced throughput volumes for the future.

The economies of scale are such that a variation in throughput volumes, measured in CGT, will have a marked effect on the overall performance in terms of cost per unit of output. For a given market rate, the throughput volume at which the cost of production equals the market rate can be assessed to ascertain the break-even point. Alternatively, for an anticipated throughput volume, the overall performance can be established to achieve break-even or a target level of profitability.

Labor Rates Shipyard labor rates are rising in most shipbuilding nations, especially in some of the Far East and East European countries. This is also happening in developing nations where the employment cost represent a high proportion of total operating cost. To maintain competitiveness, these rises need to matched by productivity gains. Target levels of productivity in terms of employee years per CGT can be established for various labor rate scenarios, establishing improvement targets over the period of a strategic plan.

Exchange Rates Similarly, the effect of exchange rate variations on the cost per unit output can be ascertained to establish the sensitivity of the business to such external factors. This is of particular importance where long orderbooks exist, and for developing countries where their strengthening economies combine to push up exchange rates and labor rates thus demanding significant increases in productivity to maintain competitiveness.

Based upon this information a target performance level can be established, in terms of the desired cost per unit of output expressed in $ per CGT. Comparing this with the current performance established in accordance with the principles explained earlier, the improvement gap can be calculated.

Development Program

Having quantified the required improvement in the form of a target performance level, the method of achieving this improvement needs to be established in terms of where the improvement initiatives will be focused to achieve maximum benefit.

In implementing technology, the objective is to raise the level of technological sophistication in a uniform manner across a business. Islands of higher technology in an otherwise less sophisticated environment generally do not reach their full potential. Weak points in the technology can dissipate or dilute the benefits of overall investment in the same way that bottlenecks in the production process throttle output.

Analysis of the technology audit results determines how uniformly technological progress has been made and highlights any low points or areas of imbalance. In such circumstances, a priority of the development program should be to address these imbalances to restore the uniformity thereby eliminating the so called islands of automation [12].

Historically, investment in technology has often concentrated on upgrading the hardware and facilities of the shipyard whilst the investment in upgrading and improving the sophistication of the management processes, organization and systems has lagged behind. The technology audit demonstrates this clearly in terms of a lower ratings in the relevant modules. In such circumstances the focus of the development program should lie in these areas.

In other instances, a technology audit shows that past investment in technology has been concentrated in certain

aspects of the business, for example in steelwork, where a high level of mechanization and automation has become the norm. However, if this has left the outfit and construction aspects lagging behind, then the full benefit of the investment is likely to be dissipated in the latter stages of the shipbuilding process. The potential for improvement through investment in appropriate, hardware or soft technological initiatives will be greater in these areas. In such instances, emphasis should be placed on considering projects which would lift the level of technological sophistication in the lower technology areas in preference to further investment in the already leading technology aspects of the business.

For certain aspects of the shipbuilding process, such as coatings technology, further assistance in identifying potential options for development is available, where specialized audits have been developed to focus on critical areas or bottlenecks [13].

Where a balanced development of technology is achieved, a shipyard tends to reap synergic benefits over and above the direct benefits of the investment calculated in the performance gradient approach.

Evaluating options Using these concepts, a shipyard management establishes a range of possible improvement initiatives, each requiring different implementation resources and resulting in varying productivity improvements. For each such initiative, the performance gradient can be calculated demonstrating the direction in which each would move the overall performance of the business on the cost curves. At this stage the treatment of technology costs becomes critical, requiring careful assessment of the economic benefit profile of the initiative to determine over what period of time and with what profile, the capital or implementation costs of the initiative should be spread.

Where the performance gradient is steeper or equal to the break-even gradient, the initiative has a beneficial effect on the overall cost per unit of output of the yard, moving the business onto a lower cost curve. However where the gradient is flatter than the break-even gradient, implementation has a detrimental effect on the business and would serve to move the yard onto a higher cost curve, thus making it less competitive.

In this fashion, the initiatives can be ranked in terms of their performance gradients to establish those which would generate the greatest benefit to the business. This information can then be used in conjunction with the results of the technology audit, and the capital or financing constraints to establish a development program for the business.

In appraising individual initiatives in this fashion, projects are prioritized on a pure cost benefit basis. Simplistically this assumes that investment capital is readily available. However, in practice, shipyards have financial and other constraints, and the situation may be more complex requiring a balance between a number of factors.

In any investment decision, the key criteria for shipyard management are likely to be financing and employment. There is a finite limit to the money available to finance technological improvements and these improvements will result, primarily, in a reduction in the demand for labor and hence a reduction in employment levels. In high technology yards, the driving force is generally the difficulty in recruiting. In these yards investment and capital financing is more readily available, and the improvement projects can be selected based upon these criteria.

However in developing countries, where labor costs are beginning to rise, the availability of capital funds to finance the productivity improvement necessary to maintain and improve the costs per unit of output are often severely restricted and may depend on government financing. Similarly the shedding of labor in such situations is likely to be an emotive and political issue bringing with it the possibility of major industrial relations issues or political intervention. The issue facing the yard management is one of balancing the availability of finance with an acceptable level of job loss, e.g. through early retirement programs whilst attaining competitive $ per CGT operating performance as dictated by the market price selling level.

The cost structure for an individual yard, reflecting its current position on the cost curves, can be used to generate a series of curves as shown in Figure 9 plotting the reduction in jobs (Y axis) against the increase in annual capital cost for a variety of $/CGT improvement levels. Having assessed the economic benefit lifetime of various improvement options, the increased annual overhead costs can be determined. These curves can be used to identify and prioritize options that can balance these twin criteria to help meet specific improvement targets.

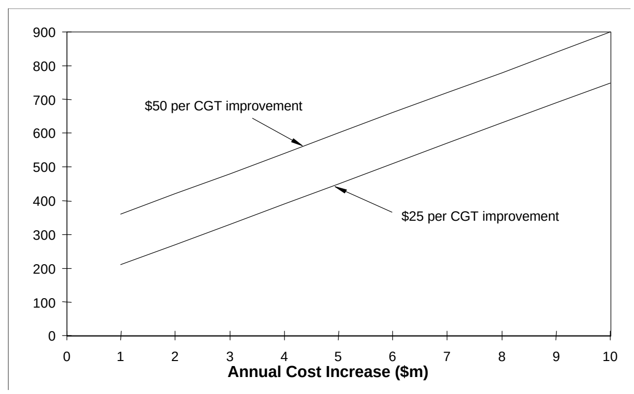

Figure 9 Constraints on development strategies

The overall impact of a group of initiatives implemented over a specific time period, can be calculated, to predict the cost per unit output of the business following implementation of these initiatives.

CONCLUSION

In relation to soft and hard aspects of technological development, it is unlikely that the full benefit of hardware investment can be obtained whilst the management and operational processes are sub optimal. Given the relatively high costs of hardware investment, improvement in the operating processes and systems generally offers low technology yards a better return for their investment.

Thus it would appear that a basic strategy for performance

improvement requires a balance between hardware investment and soft technological investment. It should follow a development pattern that uniformly raises the technological sophistication of the yard in response to the changes in the business structure and economic environment. On a commercial basis, the development program would not seek technological development as an objective, rather as a means to maintain or improve the cost per unit output as indicated by progress on the cost curve diagram.

The following examples, provide an interesting perspective on how different development strategies and economic circumstances have impacted on the trends in the current world shipbuilding capacity.

- Swedish shipbuilders backed up development in technology with excellent systems. However the rate at which labor cost increased meant considerable investment in hardware which at that time (mid 1970s) proved prohibitively expensive, or simply not available. They were unable to remain competitive.
- In the UK., some of the most modern facilities and hardware were introduced in the mid 1970s but were not supported by the appropriate investment in organization and systems. When this finally occurred in the early 1980s it was already too late.
- In Japan effort was placed on developing systems to maximize use of the hardware in place, and it has often been commented on since that time that Japanese yards are rarely equipped with the latest hardware technology, but often they have achieved a remarkable balance between systems and hardware investment.

Historically the development of shipyard technology has been a mix of hardware improvement and development of soft technological aspects with most yards on the benchmark iso-cost curve being at different stages of this cycle. Effective future development strategies must be set against the demands of the market and capabilities of competitor yards and need to be based upon a clear understanding of a shipyard's current position and the impact on the proposed technological improvements on this.

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Physiological Factors Affecting Quality And Safety In Production Environments

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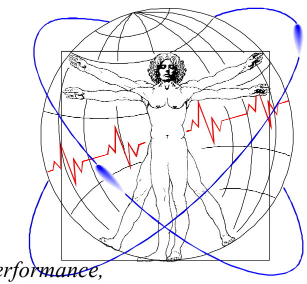

ABSTRACT

Physiological and psychological influences affect the reliability of human performance, particularly in shift work production environments. These influences affect all personnel and include in part the quality and quantity of sleep achieved, the effects of sleep loss, circadian influence and phase, time on task, consumption of caffeine and alcohol, the side effects of many over-the-counter and prescription medications, and other factors that are known to have an effect on performance, response time, cognition, memory, and mood state. These factors affect the quality and safety of the product, process and personnel, and should be considered throughout all phases of design, management and production.

NOMENCLATURE:

FIM, Fabrication, Installation and Modification
HOF, Human and Organizational Factors
OSHA, Occupational Safety and Health Administration
CFR, Code of Federal Regulations
REM, Rapid Eye Movement
NREM, Non-Rapid Eye Movement
CHD, Chronic Heart Disease
OTC, Over-the-Counter medications
process, quality, sleep, fatigue, circadian influence

INTRODUCTION

The purpose of this paper is to present an overview of the physiological and psychological influences that are known to affect the quality and safety of human performance in the Fabrication, Installation and Modification (FIM), environment. The term FIM and "production environment" may be used interchangeably herein.

These influences are considered germane to all functions, including management and administration, design, production, subcontract and inspection personnel alike. In so much as similar vigilance, performance, quality and safety are required of either in cooperation with or the absence of each other.

This review does not intend to be comprehensive. Other social and behavioral influences exist that should be considered when evaluating the safety and quality of work environments in general, and whenever changes are planned or implemented. Nevertheless, this review will highlight a selected nucleus of factors that have been determined to negatively affect human performance in the FIM and other production environments. Each of these factors have been validated to some degree through numerous research projects that have served to establish general parameters regarding the capabilities of humans as participants in, or monitors of, a wide range of tasks.

These research initiatives have spanned many operational environments and have reached sufficiently similar conclusions regarding human ability and performance for these factors to be considered an inescapable reality of normal human physiology and psychology.

Further are these influences believed to be indifferent to corporate status, wage, earning potential, experience, subjective estimates of personal professionalism, and to some degree social, motivational, and personality factors, as well.

For example, even highly motivated, strong willed, intelligent and responsible personnel, such as commercial flight crews [1], are poor monitors of mundane, slow to change, or infrequent events [2]. This is true despite that they are well educated, trained, and highly compensated, and, generally work in a less severe physical environment than the average FIM worker.

Additionally when humans become tired and or are not feeling well, tasks that require maintaining vigilance in a poor contrast environment, an environment with little or no activity, or in an environments that is very busy [3, 8], are less likely to be performed at the level that the designer of the task or system might have modeled or envisioned. Humans are also likely to adopt complacent attitudes or behaviors when required to monitor events that they have become habituated to [4], and/or systems that are normally reliable.

When considering the FIM environment, many examples of tasks and work stations that possess one or more of these undesirable qualities, exist. Examples of these include yard crane cabs, security posts, operating control stations, and others. Tasks and environments also vacillate between periods of minimal activity or involvement of the operator and periods of high demand. Frequently these fluctuations are controlled by or are expected to be

reflexive to another person, cue, or effort - often in cooperation with human and computer controlled equipment. It is therefore essential that environments, tasks and those controlling them, consider the effect that the design and nature of the work environment or task will have on the human working therein.

Typical FIM environments by their nature and geographic location often present less-than-optimal working conditions. Many of these conditions are largely beyond the control of those working in or responsible for managing them and the processes that occur within them. Nevertheless, the effects of the daily and seasonal ranges of extreme heat, cold, humidity, and vibration that are common to these environments, cannot be divorced from the quality and safety of the production process or outcome.

This is true whether the environment be ambient [5], or a confined space (such as a yard crane cab) [6], process control room, or administrative area [7]; whether they are artificially or naturally lit [8].

Given so many independent variables to manage, the essential element responsible for achieving, maintaining, or improving quality and safety remains invariably human. For this reason it is imperative that owners, insurers, designers, managers, and operators of production environments, focus on the humans operating in the FIM system as systems in and of themselves.

Further, the physiological factors discussed herein cannot be eliminated simply through training, procedural adherence, or even application of appropriate design criteria and job aides. While each contributes to the overall safety and quality of the work environment, and may modulate injury and substandard performance to some degree, these remedies alone cannot overcome normal physiology. Technology cannot ever completely compensate for or eradicate human limitations, though automation designers might prefer to believe otherwise.

While hard and software solutions hold some value as assistants to the given operation, they cannot entirely replace the human-ware in the system. Too often, technological solutions, initially believed to be the "end-all" of labor saving and efficiency applications, actually prove out to have only redistributed workloads. This redistribution typically only results in manual, tedious, or repetitive tasks being exchanged for more demanding cognitive ones [9]. The apparent reduction in workload may offer distinct advantages to users under normal circumstances, yet be more difficult to diagnose when they are not working properly. [9a]

Despite the 24-hour-a-day nature of FIM environments, the limitations and abilities of humans have largely been ignored. If optimum levels of quality, safety and ultimately profitability are to be achieved, the human factors described herein, at a minimum, should be incorporated into any Human and Organizational Factors (HOF) plan [10a]. Incorporation should be undertaken as early in the planning and resource allocation stages of a project as is possible.

HOF plans are increasingly being required in certain commercial and military contract specifications as part of the submission and award review process. It is therefore anticipated that consideration of these factors will increasingly become part of the bid review processes as well as the safety and risk reduction programs of the future.

FACTORS AFFECTING ALERTNESS AND HUMAN PERFORMANCE

The factors affecting the alertness and subsequent human performance that will be reviewed include:

- Time of Day
- Sleep and, Sleep loss
- Fatigue
- Time on Task
- Age
- Medical Conditions
- Other Influences

Time of Day

The body maintains an internal clock or pacemaker that regulates many if not all human biological functions [10]. These functions are considered a "normal function" of human physiology, and follow general to quite distinct rhythms. Many of these rhythms have

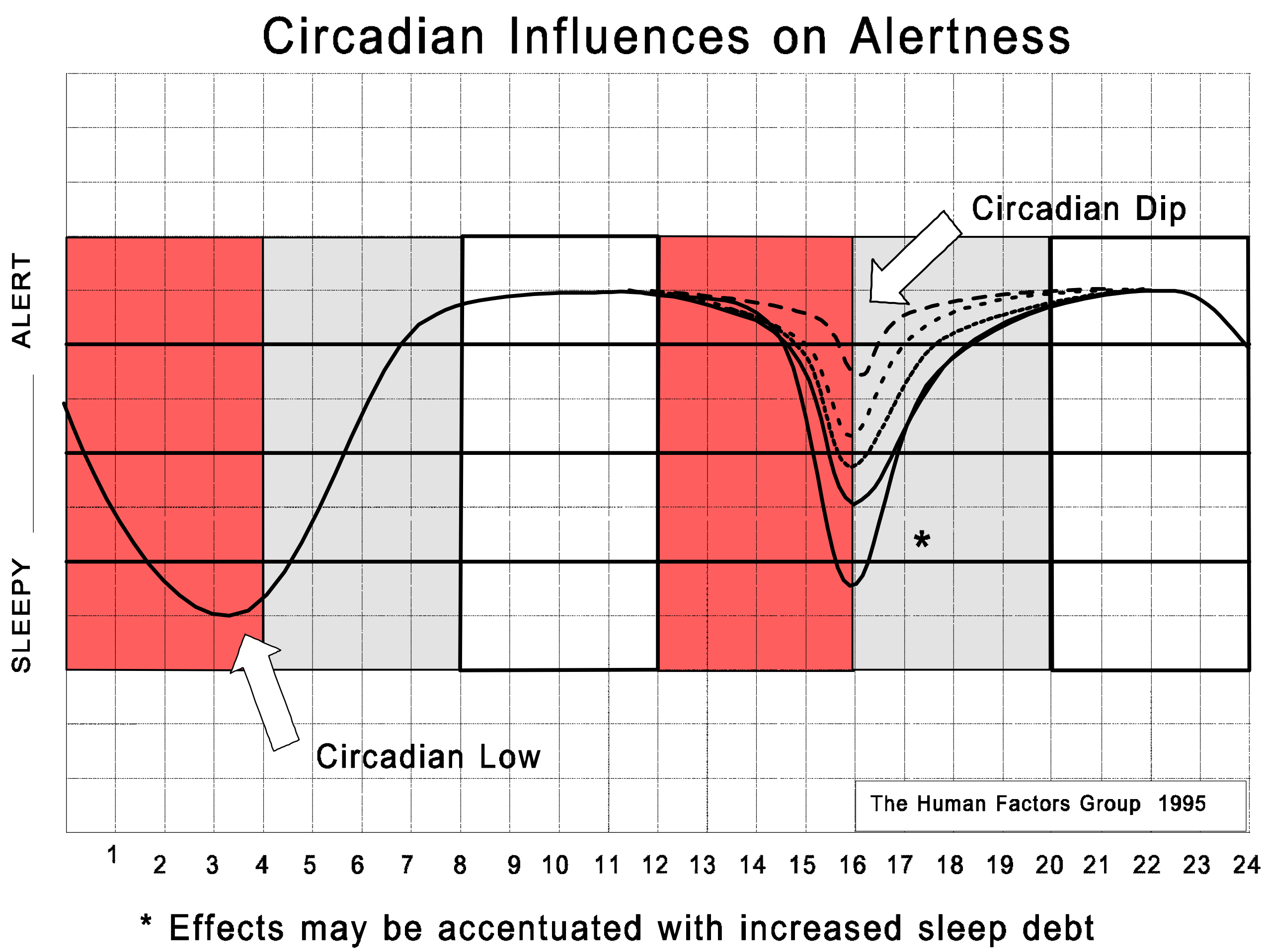

Figure 1. Circadian Influences on Alertness.

been accurately identified, separated, and plotted against time in predictable patterns. The rhythms that most concern this discussion are those that appear to follow a daily cycle and are hence called "circadian rhythms," meaning that they vary on an approximately 24 hour cycle [11] throughout the "circadian day."

Included among these are cycles of core body temperature, hormone secretion, digestion, and those which serve to promote or recall one from the state of sleep.

Figure 1. represents the summation of these cycles as a function of their effect on performance and alertness.

It can be seen that the line describing the summation of these influences has both alerting mechanisms which serve to assist or support the condition of wakefulness throughout most of the daytime-day and early evening, and shutdown signals which promote drowsiness at other times. These shut-down signals typically occur twice a day - once in the early afternoon and the other somewhere after about ten or eleven PM. The first is referred to as the "circadian dip" responsible for the “crash” that many of us feel sometime after lunch. The second begins with the sensation of drowsiness that typically precedes or otherwise promotes the state of nocturnal sleep, and continues throughout most of the night. [12]

This cycle continues whether or not the individual intends or is required to remain awake during the hours approaching either the afternoon “circadian dip” or the early morning “circadian low” described on the plot as shown.

It is important to understand however, that the circadian cycle of influence is something which is not easily changed, adjusted to a new time zone, or adapted to a new work rotation. Rather, the circadian cycle of influence is better thought of as a program which has been "hard wired" into the brain over years of human evolutionary process. It is therefore “normal" for people to be less alert and to feel sleepy at least two times a day. Periods of reduced alertness and therefore performance, may be anticipated as being centered on approximately 0300 and 1500 hours everyday. [12]

Circadian influence is therefore an inseparable function of the performance and safety of humans in any shift working environment. FIM environments are often shift working environments. All work environments should therefore consider and factor what segment of the cycle of circadian influence or "circadian phase" that routine operations are planned or conducted. Allowances and operational countermeasures should be adopted that account for the performance decrements that are likely to be observed at these times.

Though largely overlooked or discounted as simply a “fact of life,” circadian factors are also relevant in production environments wherein personnel are permanently assigned to a particular shift or

work period. Even those persons who have theoretically had sufficient time to become habituated to a given rotation, including "9-to-5" day workers, are subject to circadian influence.

As an operational countermeasure, sensitive or high risk operations should be timed in concert with anticipated periods of maximal alertness whenever possible. This precaution is recommended subsequent to numerous studies [13] that have reviewed the effects that various shift work assignments have on normal physiology, cognition, performance, mood state, rate of circadian adaptation, general health, and otherwise. The synopsis of these studies may be broadly simplified as being that:

1) Some adaptation to a given schedule or rotation is possible for most people, if the subject is given enough time to adapt;
2) If the timing of synchronizing cues, such as exposure to light, meals, social interaction, exercise and other cues are appropriate to the desired shift, *and*
3) If desynchronizing cues during the period of adaptation and thereafter are minimized or removed, *and*
4) If the subject takes personal responsibility for maintaining his/her personal life outside of the work environment in concert with the optimal pattern desired, particularly as related to sleep opportunities, exercise, meals, and bright light exposure.

If the above guidelines are not observed, some limited degree of adaptation to a given work schedule will still occur. Achieving optimal adaptation and therefore maximal performance, safety, and job satisfaction however, is complex, perhaps transient, and requires a sense of awareness and cooperation between both the persons in control of an environment, and those subject to it.

Many people working in shift work production environments such as shipyards, often revert to "normal" or approximately normal lifestyles timed in concert with the solar day on days "off." This has been observed in workers of all responsibility levels no matter what the timing or rotation between night and day "on" or "off" work periods. The net effect of this behavior is that complete adaptation is not ever likely to be achieved [13]. While managing "non-compliant shiftwork behaviors" outside of the production environment is largely beyond the control of the employer, incomplete adaptation will serve to moderate the performance of all personnel.

"Non-compliant shiftwork behavior" is defined herein as lifestyle behaviors that are engaged in at the election of the employee that serve to impede or reverse circadian or other adaptation to a shift or work rotation. Non-compliant lifestyle behaviors are often unintentional and not adopted entirely at the fault of the worker. While many workers are well aware of the symptoms and lifestyle frustrations that working rotating and evening shifts create, few are believed to understand the underlying circadian physiology that causes or could be advantaged to abate these effects.

Little if any education is typically provided the would - be shift worker at the time of assignment, and perhaps less pre-employment screening is performed than should be. Failure to educate personnel in the hazards and side effects of shift work, or to provide adequate medical screening, enables personnel to enter the production environment who medically, physically, or emotionally should not be. In fact, production environments already contain many people who are not suited to or are otherwise dissatisfied with shiftworking lifestyles, particularly night shifts.

Therefore, all personnel responsible for the design, coordination, or planning of the production environment, as well as those who are required to function within it, are urged to consider the circadian phase within which a given operation is to be conducted.

As a general rule: Time the most dangerous or demanding tasks for those periods in the day that personnel are most likely to be alert.

Sleep and Sleep Loss

Inseparable from the discussion of circadian influence and phase are the issues surrounding sleep, sleep quality and quantity, sleep loss, and recovery sleep. Treatment of these topics alone requires considerable time and explanation. A general understanding of the underlying physiology, remains of critical importance if improvements in the operational environment are to be effected. In brief, these subjects may be summarized as follows.

"*Sleep is a vital physiological function. You need to eat, you need to breath, and you need to sleep*." [14]

If the body is deprived of any of these, it will in some fairly predictable amount of time, die. No one can exist without these basic needs being satisfied and performance becomes progressively impaired in all people [15] as the duration of wakefulness is prolonged.

The average person requires approximately 8 hours of sleep [16], however some people require less and others substantially more. Regardless of the basal amount of sleep individually required, when the available sleep opportunity does not allow for an individual to achieve the amount "normally" required, "sleep debt" begins to accrue.

Sleep debt is analogous to a bank account or checking reserve that may be tapped to some limited extent, accruing in an approximately linear fashion as incurred. Accruing this debt will cause the physiologic need for sleep only to increase. This increase is described by the term "sleep pressure." Sleep pressure increases throughout the period of wakefulness and is manifested in the sensation and tendency of the body to achieve the restoration it needs and can only get through the state of sleep. The most obvious indicator of increased sleep pressure is the sensation of sleepiness. Sleepiness can be scientifically measured and correlated to the alertness of the subject being tested.

At some point in time, and particularly when alerting mechanisms are removed during declining or "de-alerting" circadian phases, the sensation of sleepiness may be so overwhelming as to cause *uncontrollable*, and often dangerously undesirable, sleep episodes. These episodes range from a mild sensation of distraction or "day dreams," to the extreme head-bobbing drowsiness and/or observable sleep episodes that most people have experienced at some time or another.

Perhaps the most alarming of these unplanned and uncontrolled sleep episodes takes the form of what is known as a "lapse" or "micro-event." These occurrences may last from fractions of a second to several minutes, and occur at any time of the day or night throughout periods of perceived or required "wakefulness."

Stimulus, information, and even conversation occurring during a "micro-event" may not register with the affected individual *at all*, even if the eyes remain open.[24] Much like the well known anecdote about "the lights being on...but nobody's home," a lapse or micro event is a state of disassociation with the environment that a person is immersed in or controlling. Disassociation with the

immediate or distant environment is not always complete. In some cases humans have been reported to be able to answer alarms or perform actions within sleep episodes or lapses, without recognition or recollection of having done so.

It is possible that humans may experience lapses during the performance of typical production tasks such welding, spray painting, or monitoring production equipment, without the individuals knowledge. Such acts of commission or omission may result in errors such as welding flaws, painted areas being over or under coated, and other errors or inefficiencies that become latent defects or must be reworked.

There are also times in any stage of the production cycle when coordination amongst participants is required if accidents or critical errors are to be averted. Involuntary performance, disassociation from the task or environment, and inappropriate acknowledgement of an action, alarm, or other cue can lead to catastrophe.

While no one can predict when a “micro event” will precisely happen, it has been determined in numerous studies that micro events are more likely to occur in people who are sleep deprived than those who are well rested. How many mistakes, injuries, near misses or accidents, or the cost of these, that are related to lapses in consciousness is unknown. It has been established that the amount of sleep preceding an incident is an important factor in accident investigation, error detection and therefore loss prevention [17].

The quantity of sleep alone is not sufficient measure of the degree of restoration likely to be achieved. The *quality* of sleep is equally if not more important than the quantity achieved. Virtually all personnel in and out of the production environment have experienced nights of "sleep" wherein eight hours of time spent in bed have not been restorative. Many people have also experienced occasions when brief naps have seemed more refreshing than longer sleep episodes. The subjective difference between the restorative value of sleep episodes of differing lengths is attributable to a number of complex factors. Including, the time of day that sleep is attempted and the effect that other factors like caffeine, alcohol, and various over-the-counter medications have on the quality of sleep possible.

Many substances alter normal sleep patterns or “sleep architecture.” The consequence of this alteration is generally poorer quality sleep and subsequently impaired or less than optimal performance thereafter. To understand the potential effects of the sleep modifying drugs that will be discussed later, it is important to understand that sleep is not a homogeneous state but divided into at least two distinct types.

The states of sleep are described by specific patterns of brain wave activity, though they are named by the degree of eye movement (rapid and non-rapid eye movement, or REM and NREM respectively) that we are likely to experience within these states. NREM may be divided into four distinct stages, 1 through 4, with stage 1 being lightest and stage 4 the deepest sleep. REM sleep is characterized as “the dream state” and as different from NREM as is sleep from wakefulness [12, 24]

Each type and stage of sleep plays an important role in restoring the physiologic and psychologic needs of the body. Depriving the body of either for some period of time by abbreviating sleep periods, ingestion of substances that modify sleep architecture, stress, or other means, will have both physiologic and psychologic effects. These effects will eventually manifest themselves during wakefulness as micro-events, depressed or altered moods, impaired performance, and in other ways..

The accepted correlation between the subjective and physiological effects of sleep loss as related to extended periods of wakefulness, the quality and quantity of sleep achieved, or otherwise, is embodied in the study and sensation of "fatigue." [18]

Fatigue

Fatigue as it is used in this context, is a general description of those factors that cause or contribute to performance decrements in humans as a result of extended operations, shift work, transmeridian travel, sleep deprivation, personal stress, and other factors [18]. Factors contributing to fatigue are considered intrinsic to any production environment.

Fatigue can be experienced and expressed in both physiological and subjective terms and may be measured fairly accurately in a controlled environment. Symptoms of fatigue include drowsiness, burning or itchy eyes, headache, back pain, stress, anxiety, depression, alienation, attention deficit, the inability to concentrate, memory loss, confusion, mood swings, and gastrointestinal disorders, amongst others.

These subjective expressions of fatigue may be further quantified to include observable symptoms very similar to those following alcohol consumption. These include:

- loss of balance and disequilibrium
- selective exclusion of inputs
- fixation on selected inputs
- inappropriate risk behavior and/or assessment
- shift from external to internal focus
- depressed motor skills and coordination
- increased subjective error tolerance
- exaggerated corrective action and overcompensation
- decreased cognitive ability
- increased reaction time
- global performance decrements, including
  - reduced visual acuity,
  - oral detection and discrimination, and
  - other sensory related impairments

The symptoms described above have significant effects on the safety of the production environment. It is of fundamental importance that persons responsible for the control of any production environment recognize that *no one* is immune to the effects of fatigue.

Most people will not generally admit feeling or having experienced these symptoms however until long after the effects have obviously manifested themselves in their affect and performance. This is particularly true in production environments wherein a sense of imperviousness or superhuman capability has been forged as a desirable identity. The behavioral tendency or trait associated with this denial process is sometimes described as the “Superman phenomena.” In fact, the process of denial associated with fatigue may be as strong as it is amongst individuals who are addicted to nicotine, alcohol, caffeine, and other substances [1].

Resistance levels to the admission of fatigue has both physiological and psychological origins. A fatigued person cannot feel or perceive the same sensations as a normally rested person, either within or without of the body. Consequently, fatigue affects subjective assessment of wellness and fitness for duty. Much in the same way that the neurologic effects and psychological based denial processes that attend the chronic abuse of alcohol and other

substances, serve to bias personal subjective recognition [19] of the disease process. The last person to recognize fatigue, and often the most unreliable person to ask regarding personal performance, is the individual that is already tired [12]. This is true for many reasons including the alerting mechanism that just asking an individual represents. Psychosocial factors also effect the objectivity of responses. Concerns for job security, social acceptance amongst peers, and certain cultural factors serve to inhibit truthful responses from many people. Supervisors and managers cannot rely on personal subjective estimates of fatigue or alertness when evaluating the fitness for duty of personnel or the safety of an operation.

Fatigue also affects risk perception and risk taking behavior. Fatigued persons are more prone to fail to recognize, inaccurately asses, or choose to take risks that a normally rested person would consider inappropriate to the circumstance [20]. The shift in risk sensitivity and acceptance may occur simply to “get it over with,” [12], presumably to get some sleep thereafter.

The effects of acute fatigue may be mitigated by a variety of operational countermeasures, including strategic napping, caffeine, and certain drugs [12]. Many countermeasures are easily and inexpensively implemented in the production environment. Countermeasures are particularly effective when augmented by survey tools and general awareness training programs specifically designed to explain the role and importance of physiological factors on human performance.

It is not possible to maintain performance via countermeasures indefinitely however. At some point in time nevertheless, the individual must be removed from the operational environment and given the opportunity to achieve preferably nocturnal sleep, or sleep appropriately timed in concert with their adapted rhythm.

Typically, restoration to “normal” performance may be achieved after two nights [21] of nocturnal sleep, though this may vary from person to person and is interrelated with the quality of sleep achieved during that time.

Repetitive abuse of the body via sleep deprivation, indigenous and prolonged operational stress, rotating shifts, and/or abusive lifestyle habits such as excessive alcohol consumption, [22] will lead to the condition or state of “chronic fatigue.” Chronic fatigue results in an overall decrease in performance, wellness, and emotional state that may be difficult to impossible to rehabilitate by sleep alone [23].

Figure 2 has been included to demonstrate how sleep maintenance or loss may be compared to performance over time. The top line represents the probable performance of a person that is allowed to achieve as much sleep as physiologically needed, known as “sleep satiation.” Sleep satiation is very hard to achieve in today’s modern society. It is estimated that a substantial portion of the American society [14, 24] does not consistently achieve satiation, even when working normal “9-to-5" jobs and living a typical lifestyle. Shift workers in many production environments have also been determined to accumulate sleep debt. Achieving sleep satiation is therefore considered difficult, second jobs, grad school, children, and recreation not withstanding.

The middle line in Figure 2 represents a person who is allowed enough sleep to maintain some lesser level of sleep satiation and therefore performance. This less than optimal level may or may not be adequate to guarantee their performance in a given production environment. By far the majority of production workers fall into the middle category in so much as they would probably be able to achieve more sleep if time were available. Hence, their performance would likely be improved [24] by doing so. Humans routinely perform tasks at differing levels of sleep deprivation. Typically this performance may in fact be “adequate” enough to “safely” drive a car to work or otherwise function as a member of society. No estimate or evaluation is made as to whether this level of performance is appropriate to the requirements of the production environment however. Even if a production environment requires driving the same or similar vehicle as part of the work environment, the same degree of freedom, safety margins, and operating guidelines do not exist in both environments. Neither are the risks inherent to either environment the same or as clearly defined.

The bottom line in Figure 2 shows a person who becomes successively sleep deprived by only one hour per day less than is required to maintain performance at their normal “adequate state” or equilibrium. It is clear that such a person is quite sleep deprived and obviously impaired at the end of the week .

Performance at this level of sleep deprivation is inadequate in an environment that requires maximal alertness, response, and/or productivity. The degree of impairment observed in humans subsequent to seemingly small but cumulative amounts of sleep debt raises some poignant questions in the production environment.

What is the appropriate length of a work week, and individual shift, and the length of time one remains on, or has to adapt to, a given rotation? The answer to this question is in part embodied in the study of performance as a function of work duration, which is often referred to as the study of “time on task.”

Time on Task

If fatigue is discounted as a factor in a normally rested person, how long can he/she remain on task before performance is observed to decrease to a level that is considered unsafe or inefficient? The exact answer varies with each individual and will vary within the same individual depending on the circumstance and the demands of the operational environment. Some generalizations may be applied to all people nevertheless, which are synopsized as follows.

Routine operations. No matter the length of the work period or shift, the amount of time “off,” or the amount of time off watch but on call, schedules need to be designed and arranged to allow personnel to achieve their basal sleep requirements. Time off should be of sufficient duration as to allow personnel time enough to achieve preferably one consolidated sleep episode provided in concert with their personal daily rhythm. Additional time should also be provided however is required to allow employees to accomplish tasks that are typically required of “normal” members of society. Particularly in the case of production environments that also maintain a resident staff or perform work on the road, sufficient “off” time for travel, personal hygiene, laundry, meals and digestion prior to sleep should be provided as well. When operational demands such as those arising in response to production deadlines, emergency repairs, or natural disasters, cannot provide for all or even most of these considerations, the potential for sleep debt to accrue is increased. Consequently the likelihood that human performance, reliability, and mood will at some point deteriorate is considered inescapable.

No universally accepted work-rest guidelines are known to exist in or for the production environment, though various regulatory and labor union guidelines have exist for some time.

Other operational environments have studied the issue of time on task in some depth however. For example, in the commercial air transportation industry, research by NASA and others have lead to guidelines being published [21] which suggest that not less than 10

consecutive hours of rest be provided personnel following a duty period of not more than 10 hours.

Where this cannot be provided, and/or when work periods engage or approach times of circadian low (between 0200 and 0600 hours), rest periods should be increased to allow more recovery time. In cases where extended operations and prolonged periods of wakefulness are required, not less than two nights of recovery sleep should be allowed prior to reassignment.

These recommendations are not considered extreme and parallel the normal eight hour shift or business day that members of the management and administrative staff typically serve. Many organizations require production workers to work four ten or even twelve hour shifts however, particularly in response to seasonal demands or opportunities to do so. As do many production environments require or encourage overtime hours to be worked on a routine basis. These practices have the same net effect on the employee however, by extending time on task and therefore reducing the amount of rest and sleep opportunities available thereafter.

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Present guidelines also assume that all employees work in a relatively comfortable environment, which means one that is not uncomfortably hot, cold, noisy, excessively vibrating, or that requires some unusual or strenuous posture or physical work attitude.

Environmental factors alone may cause a person to fatigue quickly, internalize thoughts and focus on the stressor to the detriment of other sensations, inputs, and information. Further do present guidelines presume that the employee is able to maintain a normal eating pattern, remains hydrated, and can relieve themselves when required.

Where these environmental conditions and personal accommodations are not provided, and there are others not mentioned that are similarly important, then performance and efficiency will be dramatically reduced at some point.

Routine schedules and environments should be reviewed and structured to minimize the probability that fatigue will accrue beyond levels that may be rehabilitated by the off or sleep time available thereafter.

Sustained Operations. Where the work-rest provisions referenced above cannot be maintained over prolonged periods of time, which is defined as greater than 2-3

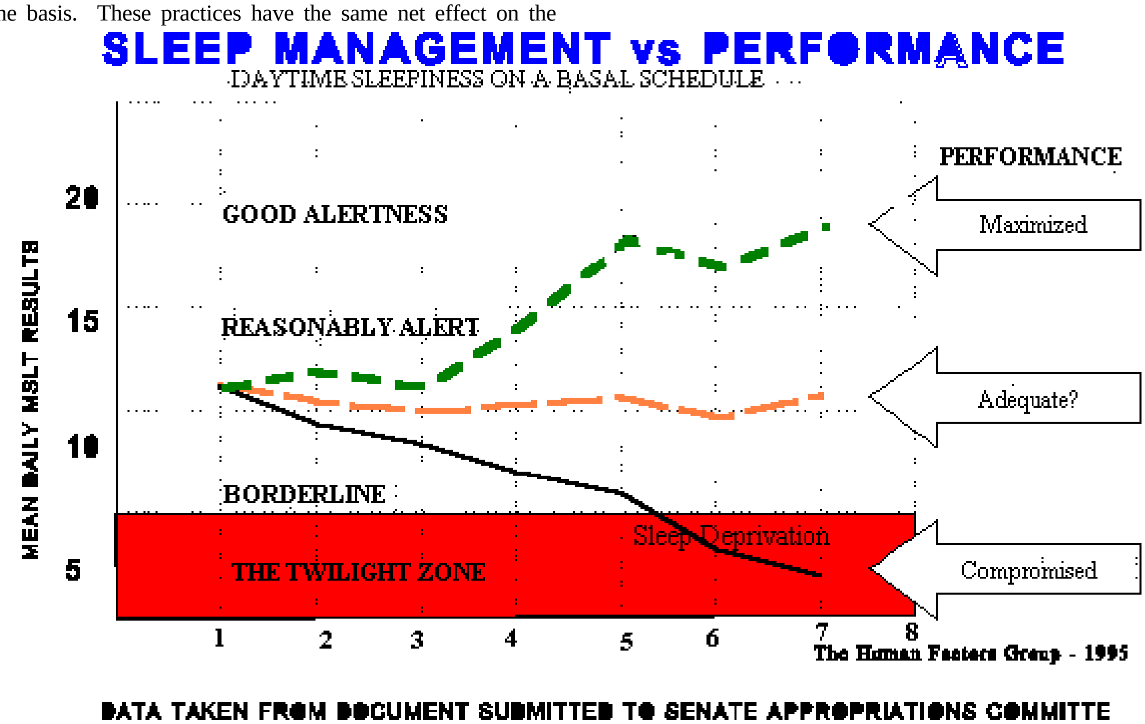

Figure 2. Sleep Management vs Performance

days for the purposes of this discussion [15], performance will deteriorate. Recent study of the brain's ability to metabolize glucose, which is the fuel required to sustain basic cerebral functions, has determined that a dramatic decrease in *global* brain functionality occurs at approximately the 18 to 24 hour of wakefulness mark. [15]

This decrement affects all major brain functions that are considered important to vigilance, performance, and reliability. Including those associated with cognition, eyesight, hearing, coordination, and other senses.

Regarding the study cited which was performed by the Walter Reed Army Institute of Research, the subjects tested were 21-29 years of age, in good health, and possibly in better physical condition than the average production worker. Subjects also

remained in a controlled environment for the duration of the test. Subjects therefore did not leave the test to moonlight at second jobs, use or abuse recreational drugs like alcohol, maintain familial responsibilities, or engage in excessive physical activity after work.

In considering the significance and relevance of this study to the production environment, the results may represent a "best case" scenario. It is likely that the average population in a production environment therefore experiences at least the magnitude of the effects reported. Significantly greater performance decrements may be observed in production workers when multiple performance modifying influences such as alcohol are considered in addition to the effects of sleep loss resulting from extended periods of time on task.

Nevertheless, the results of this study demonstrate that no person should be expected to remain functionally awake in an operational setting for an extended period of time. Restorative sleep opportunities must be provided and utilized for sleep. Oddly, anecdotal survey of military personnel engaged in sustained operations has suggested that it is the highest level of command who are most likely to subject themselves to extended periods of wakefulness. This statistic leaves one to question whether command decisions made during day two, three, and so on are as considered or rational as would they have been if sleep had been designated as an operational priority, as well.

In the production environment it remains only academic to relate the military anecdote provided, to the stresses that deadlines, critical path maintenance, milestone inspections, launchings, and sea trials all give rise to.

Where commercial viability may be the "war" being fought by management and supervisory "commanders," with production worker "troops," it cannot be ignored that real lives are nevertheless at stake. Responsibility for the quality and safety of the product or service begins in the design and fabrication stages of any product and extends throughout the operational life cycle of the product (vessel), thereafter.

For these reasons, extended periods of service, including "all-nighters" undertaken by the design staff, are to be avoided. Prolonged periods of overtime or even *volunteer* time should also be curbed in the interest of safety, quality and overall productivity.

Many in the production environment would argue that overtime is an inescapable, if not financially desirable reality of equipment failure, supply shortages, change orders, and other delays. Those bearing fiduciary responsibilities might wisely review why these hours are required in the first place. Some percentage of extended work periods are considered inevitable, though personnel should be managed to ensure that fatigue does not become the root causes of further delays, accidents, degraded performance, safety and quality overall.

Age and Performance

One of the most controversial subjects regarding human performance centers on the issue of age as a function of ability, cognition, vision, reflexes, and performance overall. This controversy is to be expected considering the aging nature of the American workforce, and for a variety of psychosocial reasons as well. Valid arguments regarding the role and value of experience, training and professional skills achieved over time exist that oppose arguments in favor of the physical benefits that youth to some degree affords. This review will dealing with age related performance strictly as a function of normal aging.

It is well established that there are certain clear physiologic differences in humans of varying ages that affects their ability to perform as they grow older. One significant difference between normal older and younger humans is related to the ability of older people to achieve and maintain the state of sleep.

Throughout life the quality and quantity of the sleep people can achieve changes as does their ability to achieve consolidated periods of nocturnal sleep. Even as early as age fifty or so [18, 25], undisturbed sleep periods get shorter and there is an increased tendency for daytime napping.

The inability to achieve undisturbed sleep affects both the quality of daytime alertness and the ability of older people to achieve quality recovery sleep. The performance decrement which may result is only exacerbated by evening or irregular shift work in general, and following prolonged periods of sleeplessness.

Physiologic sleep needs do not substantially change through adulthood. Only the ability to achieve the states and stages of sleep changes. Older persons still need to achieve their basal sleep requirements. Many older persons subjectively experience and rate the effects of sleep loss significantly higher than would they have earlier in their lives.

Other physiological changes occur as a normal function of aging as well, each of which affect our ability to perceive the environment we are part of. Changes typically occur in eyesight that may be generalized as decreases in our visual acuity when observing moving targets [26], whether they be moving by us or we them.

Significantly higher degrees of contrast are also required to achieve the same visual acuity at age fifty as would a twenty or thirty year old person require in similar environments. Glare sensitivity also increases with age, and farsightedness may progressively develop throughout life, becoming more noticeable after age 40 or so. [8, 27].

Humans also tend to be less tolerant of heat stress as they age, particularly if they are in poor physical condition or consume alcohol before or during exposure [28].

These normal changes are not presented to jade or otherwise color the practice of employing people of any given age bracket. These examples are simply intended to emphasize the importance of these human factors in the production environment when considering the task and level of performance required.

Clearly, expecting an older individual stationed in a hot operating station, such as in a security post or crane cab [6] overlooking the glaring water, to maintain vigilance and/or detect sudden or quickly developing changes in an operational setting that is generally serene, would be a less than optimum match of human and task. Tasks and environments should be designed with both the work environment, the operator, and the variability in operators in mind.

Medical Conditions

Certain medical conditions exist which affect the ability of humans of any age to perform in the operational environment. These include obvious physical restrictions such as heart disease and general obesity, whether genetic or otherwise in origin. Less obvious medical conditions exist that impair human performance in the production environment. These conditions often exist without the subjects awareness.

Of these, sleep disorders such as excessive snoring and sleep apnea are most likely to exist without the subjects knowledge. Clear correlation between the sensation of excessive daytime sleepiness

and/or the associated performance decrements experienced during waking hours is therefore often not made by individuals and physicians.

In the case of excessive snoring and sleep apnea the affected person is unable to achieve the stages of sleep required to ensure physiological and psychological restoration. This occurs essentially because the act of snoring and the cessation and re-commencement of breathing, act as alerting mechanisms and cause repetitive awakenings. Awakenings prevent consolidated and deeper stages of sleep.

A significant percentage of the population is believed to suffer from these and other sleep disturbing disorders. It is further estimated that many of the symptoms of prolonged sleep impairment, such as hypertension and CHD, are treated without the root cause ever being identified as sleep related.

Unfortunately, many of the medications prescribed have sleep inhibiting side effects that treat the symptom observed but only further worsen the underlying root cause.

Many people also suffer from "insomnia," either as a medical condition or as a transient symptom that is most often psychological in origin and associated with life-stress. Shift workers also complain of recurrent insomnia when attempting to adapt to changes in work rotations.

In response to these complaints a variety of sleep promoting formulations are prescribed. These include medications that either help to promote or maintain consolidated sleep. Many sleep medications alter sleep architecture however and it is important to select the appropriate drug for the operational environment envisioned.

Of specific concern is the half-life of the drug in the system, as well as any rebound effects which may follow use and "carry over" into the production environment. As a general rule, it is best to take only the ***"lowest effective dose for the shortest possible time"*** [12]

Other Factors

Many other factors serve to impair quality and safety of a production environment. Some of which are the direct result of countermeasures specifically designed to avoid this from occurring.

Of these, three stand as most significant and likely to be observed in the production environment. These are caffeine, alcohol, and various OTC medications that are readily available, widely utilized and often little understood.

Caffeine. Caffeine is an effective stimulant, however it is easy to unknowingly abuse caffeine, often to the point of developing a dependency to the drug. While coffee is perhaps best known and the most widely used operational stimulant, some types of tea in fact may be brewed to deliver more caffeine per serving. Caffeine is also present in a variety of innocent foods, such as chocolate, cocoa, and most cola-based soda. Table One has been included for reader reference [29], and demonstrates the manner in which certain products such as Mountain Dew® may contain significant amounts of caffeine, despite that some products are not classically thought of as stimulants. What many caffeine users do not realize is that humans develop an almost immediate tolerance to the drug. A given dose routinely administered, be it in the form of coffee, soda, or caffeine pills, will not have the same effect as did the first or second administration [16]. Habituation to caffeine occurs quickly. Many psychosocial processes are associated with the addiction process as well. Certain of these serve to facilitate the normal human tendency or

Brand	Caffeine	Brand	Caffeine
Mountain Dew	52	Diet Pepsi	34
Tab	44	Coca-Cola	34
Sunkist Orange	42	7-up	0
Dr. Pepper	38	Sprite	0
Diet Dr. Pepper	37	Diet 7-up	0
Pepsi Cola	37	Hires Root Beer	0

Table 1. Caffeine Content of Various Products

desire to maintain some repetitive state or sensation. This desire in turn leads to increased dose over time and dependent behavior rapidly develops.

Caffeine abuse has many side effects. Including, induced tension, headache, mood swings, vision impairments, anxiety, and central nervous system interference. Caffeine also impairs sleep onset and modifies sleep architecture. For this reason, caffeine consumption should be limited to times of operational necessity and avoided several hours prior to planned periods of sleep.

Alcohol

Alcohol is a drug that is easily sourced. Repetitive use often leads to substance dependent or abusive behaviors. The negative effects of alcohol on the central nervous system are well known however, and include increased response time, loss of equilibrium, and general cognitive impairment. Alcohol is also one of the most widely used recreational, relaxation and sleep aides in the United States, even by people who admit that they are already tired.

The FACT is that alcohol is a powerful sleep *suppressant*, and that the sleep promoting effects which are seen as initial benefits, are actually short lived. Specifically, alcohol modifies sleep architecture generally by suppressing REM sleep, and by causing frequent awakenings for a variety of reasons. These include withdrawal effects that are normal to metabolizing the drug, and awakenings stimulated by the need to relieve bladder pressure. Periods that might otherwise be advantaged by sleep or less physically taxing/damaging activities should not include excessive alcohol consumption.

Despite these facts, and despite the random testing programs and strict operational and legislative controls in effect, the use/abuse of alcohol is somewhat pervasive in production and corporate environments.

Of significant concern is the excessive recreational use of alcohol during meal periods and "after work" or on "days off." Many individuals also believe that alcohol consumed in moderation, particularly at meal times, will not effect their performance enough to be considered of significance in the work environment. Subjective

estimates of blood alcohol concentrations of ".04" or otherwise established maximum "safe" limits, are not guarantee of safe performance in the production environment. Many users of alcohol incorrectly believe that:

- Recreating with alcohol in close proximity to scheduled work periods is of no consequence, so long as enough time is allowed to "sleep off" any excess blood alcohol concentration they may have achieved, and
- That "sleep" thus promoted, is in fact restorative enough to return them to "safe" levels of performance, though admittedly not necessarily at "peak efficiency."

Such "normal" or "reasonable man" behavior can be demonstrated to result in personnel of all status reporting for work at or in excess of allowable blood alcohol concentrations, surveillance and random testing notwithstanding. Excessive consumption of alcohol will amplify existing sleep debts and result in further accumulations of sleep debt. As described earlier, this debt will have to be repaid by recovery sleep at some time, and possibly promote the occurrence of micro events and even observable sleep in the production environment.

Further may alcohol and loss of sleep modify personal estimates of risk and risk perception. This shift in risk perception does not categorically result in increased risk taking, but may do so.

Particularly within several hours of planned sleep episodes, after periods of prolonged wakefulness, and during work periods, the consumption of alcohol is strongly discouraged.

Over-The-Counter (OTC), Medications

Many people self medicate, at least initially, when they are not feeling well. Many OTC medications are available to the public, some of which have been recently released that were previously available only subsequent to the advice of a physician, by prescription. A wide variety of formulations must now compete for market share via marketing strategies aimed at achieving consumer loyalty, defeating generic availability, word of mouth advice, and otherwise. This plethora of products leads to confusion on the part of the user, and potentially inappropriate drug selection and administration. In part this confusion is promoted by products and packaging that does not effectively communicate the intended use or potential side effects of ingredients.

For example, products offering cold and flu symptom relief often contain alcohol, caffeine, or both, as well as other ingredients which serve to interfere with sleep and performance while "awake." Many products also advertise components in manners that are not universally used by industry or understood by the consumer such as "No-Drowsiness" or "PM" formula descriptions.

Other products promote drowsiness purposely or as a side effect, including some well known allergy, sleep, and motion sickness formulations. In part these effects are related to the ability of certain drugs to affect the central nervous system, which may mean that response times are increased. Clearly where machinery, cranes [6], high pressure spray equipment, and welding/cutting operations are concerned, this impairment is potentially dangerous, as well as operationally inefficient.

Personnel engaged in these operations should consider the effects that all medications may have on their vigilance, response time and performance, before they are ingested. Management should educate personnel in types and availability of drugs that are "safer" to use than others, such as Seldane™ and others that do not cross CNS barriers [1, 19].

Nevertheless, reactions to dose and type are individualistic and all medications should be "ground tested" either at home or out of the sensitive environment, prior to their being utilized in the production environment.

Certain OTC medications have been recommended for occasional use as sleep promoting aides during times of transient insomnia. One such drug, diphenhydramine, is sold under several names including Benadryl.™ This particular drug promotes drowsiness in many people without long lasting side effects. It may be taken occasionally in anticipation of sleep when mid-sleep period operational demands are not anticipated.

All drugs, including caffeine, alcohol, prescription and OTC medications have "half-lives." The half - life of a drug should be determined and considered in the timing of administration, prior to ingestion if hang-over effects are not to invade periods of required alertness and performance.

CONCLUSIONS

Normal physiological and psychological tendencies exist which should be factored into the design, planning, management and operation of FIM environments. These include in part the time of day, circadian phase, time on task, fatigue, age, and the use or abuse of substances that are considered a normal part of society. Many employees do not understand the significance and effect of these factors on their safety, health, and performance. Further is there a general lack of knowledge in the production environment to the effects of shift work on the body as a whole. This lack results in "non-compliant" shift work behaviors both on and off the work site.

Certain psychological, psychosocial and cultural factors serve to complicate treatment of these issues, as misconceptions are well established and pervasive. Nevertheless, these factors play an important role in supporting or undermining the alertness, vigilance, reliability, and ultimately the quality and safety of production personnel. Sustained and overtime operations are attended by progressive performance decrements. Overtime and extended operations, even when voluntary, should be limited in the interest of safety and efficiency.

These important considerations should therefore be factored for in the design of the physical and organizational structure of the production environment however possible. Present OSHA regulations and industry standards do not provide sufficient guidance to prevent the effects of, account for, or otherwise implement effective countermeasures against these factors. Owners, operators, subcontractors and other stakeholders in the production environment are therefore encouraged to address these issues internally and publicly in advance of regulation.

Not discussed in this presentation remain many issues that are also directly related to the reliability and efficacy of any production and risk management system that are not exclusively physiologically based. Neither have the effects that fatigue has on mood state, risk taking behavior, and communications been adequately treated.

These intentional omissions and considerations notwithstanding, the two single most effective improvements which can be most economically applied to improve the safety and efficiency of the production environment overall, include:

- Educating those most affected by or in the operational environment, their support systems, co-workers, and families

in the underlying physiology surrounding human performance, and the lifestyles associated with shift work in production (FIM) operations, and

- Sleep.

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Environmentally Acceptable Corrosion Resistant Coating For Aluminum Alloys

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ABSTRACT

A coating system is described that is based on passivation of aluminum alloys by application of Lithium salts as pigments. The resulting composition and morphology of coating films are discussed. Pigment selection applying Greco-Latin Squares statistical method to evaluate corrosion as a function of current flow on 6061-T6 test surfaces was performed. The test device is a potentiostat made by Princeton Applied Research. The pigment is an Aluminum-Lithium powder which has been surface enriched with Lithium by heating under an argon blanket and subsequently treated with the selected anions. The author calls this process "nanostructural inhibitors." The vehicle in this case is a lithium silicate inorganic water soluble matrix which becomes water insoluble upon drying. The vehicle is commercially available. Testing by an independent laboratory to ASTM B117 for 168 hours of scribed panels showed no corrosion on various alloy substrates with and without topcoats.

KEYWORDS: Coating system, passivation, aluminum alloys, potentiostatic selection, lithium salts, nanostructural inhibitors, lithium silicate.

INTRODUCTION

In the 1980's an alloy of aluminum which contained lithium was being considered as an alternate to the 2219 alloy used in aerospace since it offered about a 10% weight savings for the weight conscious designers. The product was available from France, Russia, and Australia. No American companies had pilot plant production at the time. The English were producing some small scale aluminum/lithium alloys. They could be riveted, but welding was limited by the volatility of the lithium. Some applications required welding, such as hydrogen gas tanks, where riveting was not sufficient to contain the gas molecules. This was not considered a limitation but rather a challenge to the engineers.

Another potential problem was the reactivity of lithium. As the lightest of the alkali metals, it was assumed that the alloy would exhibit some of the reactivity characteristics of sodium metal. This was especially a concern by the corrosion engineers.

However, to their surprise, when similar alloys with and without 3% by weight lithium were tested, the one with lithium proved to be more corrosion resistant.

Chromium compounds provide outstanding corrosion protection for certain metals. Chromates are used in the chemical conversion coating of aluminum (MIL-C-5541). Chromates have reportedly been determined to be carcinogenic and therefore a replacement for them is currently being sought. Environmental agencies limit the amount of chromium ion tolerated in waste water to less than one part per million. Thus, an environmentally benign replacement is desired. Since most available corrosion inhibitors are based on heavy metals or reactive amides, the available alternates appear to fall short of the desired performance in corrosion inhibition and/or environmental suitability.

Ships require primers for aluminum which can be applied by shipboard personnel while on patrol. The desired product must be a fire retardant, general purpose primer which will be both protective for the exterior as well as the interior surfaces of aluminum. Material selection and usage are rigidly governed by codes, for example, those contained in proposed contaminant restrictions.

Buchheit [1] reported that lithium carbonate in solution protects certain metals, particularly aluminum, from corrosion by reacting at the surface. Analysis by a Secondary Ion Mass Spectrometer (SIMS) confirms this phenomena. Sodium carbonate and potassium carbonate reactions produced a soluble product and no alkali was detected on the surface by SIMS. Because of their high solubility and reactivity, most "alkaline metal" compounds are not suitable for corrosion protection. Metallic aluminum normally provides its own corrosion protection due to its tendency to form an aluminum oxide insulator on the surface, but the matrix of hydrated aluminum oxide is penetrated by chemicals such as NaCl, acid, and bases.

Certain aluminum-lithium alloys demonstrated some diffusion of lithium to the surface of the alloy. The lithium ion is so small that it penetrates the large interstitial spaces of the aluminum oxide layer. The aluminum-lithium alloys are stable in chemical composition at ordinary temperatures, but a lithium-rich surface can be easily produced by briefly heating the alloy to facilitate the migration.

It appears that certain lithium alloys or compounds can be incorporated into a paint vehicle or otherwise deposited on the surface of aluminum alloys to provide corrosion protection when exposed to salt water, humidity, and other corrosive environments.

The corrosion propensity of the various alloys of

aluminum may be measured by electrochemical techniques. The imposition of a controlled potential via a potentiostat is a very attractive concept from a reaction kinetics point of view. Furthermore, electrical currents are simple to measure and can be directly related to electrochemical reaction rates.

TEST PROCEDURE

The fundamental piece of equipment used in this part of the program was the Model 352/252 Soft Corr™II Corrosion Measurement & Analysis Software manufactured by EG&G Instrument Division of Princeton Applied Research.

The instrument was installed and qualification tests per ASTM G-3 and G-5 [2] were performed to ensure the proper function.

A series of chemicals was selected and purchased for the passivation tests. Substrate aluminum panels were selected. Some aluminum-lithium was ordered in both powder and plate form. Some vendors are reluctant to send certain aluminum-lithium products since they are considered confidential.

The American Conference of Governmental Industrial Hygienists in their 1994-1995 "Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices" [3] does not list lithium compounds as particular problems, although the subject has been studied in connection with batteries, ceramics, and as an absorber of atomic particles in nuclear reactors. Only lithium hydride is listed on the Threshold Limit Values (TLV) list.

Generally, the lithium compounds are not considered toxic, depending on the anion. Lithium hydride, lithium hydroxide, lithium fluoride, lithium chloride, and lithium selenite, to name a few, are toxic, largely due to the toxicity of the anions. Lithium is a common element and many of the salts such as acetate, benzoate, borate, carbonate, lactate, nitrate, and sulfate are commercially available and regarded as environmentally acceptable. The overall toxicity is determined when the final formula is selected. The paint vehicles were chosen from those which are environmentally most acceptable.

Aluminum-lithium powder is a fundamental material studied in this project. It is available from several sources but most require orders of substantial quantities. One source confirmed that patents being sought by manufacturers create some limits. The material is commercially available, but quantities limit the variety since a minimum purchase can be $5,000 to $10,000 worth of material. However, enough was available to complete the study.

INHIBITORS

A variety of lithium salts were selected and ordered as potential pigments which would not present a pollution problem. The objective was to suppress corrosion of aluminum and possibly steel with a satisfactory substitute for chromium to avoid environmental problems.

Such materials as lithium molybdate, lithium nitrate, lithium carbonate, lithium formate, lithium acetate, lithium sulfate, lithium citrate, and lithium hydroxide were included. All of these salts of lithium passivated to some extent. Combinations were sometimes more effective than the individual components. To optimize the combination of these salts for corrosion suppression, "Greco-Latin Squares" statistical methods were used. Figure 1 shows a curve comparing the individual passivators versus the blend. Generally, the less current that flows the less is the

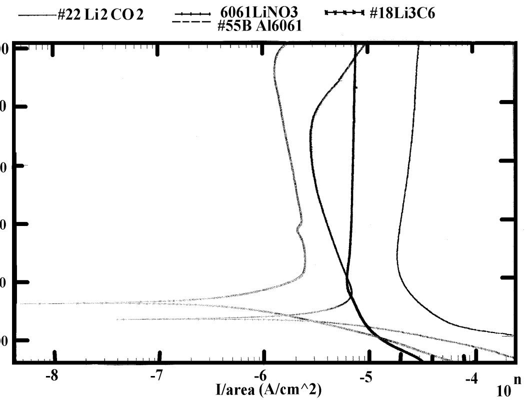

Figure 1. Anodic polarization curves (from left to right) for aluminum alloy AL6061 in 0.05 M/l blend solution, Li_2CO_3, $LiNO_3$ and $Li_3C_6H_5O_7$ (lithium citrate) individually.

corrosion. Notice the abscissa is exponential and the curve to the left has considerably less current, hence less corrosion.

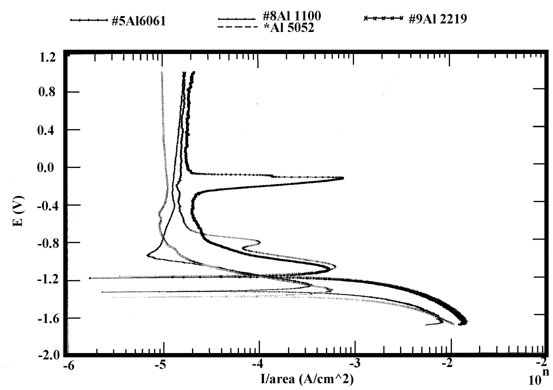

Figure 2. Anodic polarization curves (from left to right) for different aluminum alloy Al 5052, Al 6061, Al 1100 and Al 2219 in lithium citrate 0.05 Moles.

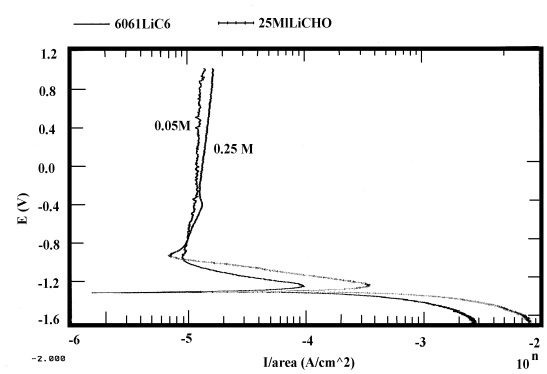

Figure 3. Anodic polarization curves (from left to right) for Al 6061 in 0.05 Moles lithium citrate and 0.25 Moles lithium citrate.

Most of the tests were run on 6061-T6 aluminum. Other alloys were tested to determine if they could also be passivated. The high copper content of the 2000 series aluminum alloys makes

them susceptible to pitting corrosion and are, therefore, difficult to passivate. Figure 2 shows some results.

Concentrations of the salts within limits do not exhibit a large influence on short term passivation as indicated in Figure 3.

NANOSTRUCTURAL INHIBITORS

Another concept which shows promise is to heat aluminum-lithium alloys (about 3% lithium) to 350^{o} C for 30 minutes in argon gas. This relocates the lithium onto the surface of small (200 to 320 mesh) pigment particles. In this way, the passivating lithium salts can be concentrated on the surface. In many instances, only the pigment surface produces passivating influences on the substrate. Since molecules on the surface are a very small percentage, on the order of one atom to ten-thousand interior atoms, the amount of passivating chemical can be much less. A patent application is also being prepared on this concept, called "nanostructural inhibitors."

Two phenomena occur which can be adapted to pigments. First, the lithium near the surface provides galvanic protection. Secondly, the lithium on the surface is very reactive and it can be a source for passivating salts of lithium.

The heated surface of the aluminum alloy is up to 90% lithium. For each surface atom there are 5,000 or so inside the paint pigment particle.

SURFACE MICROSCOPE

Surface inspection of the aluminum lithium alloy panel and treated aluminum lithium alloy panels provides evidence of reaction products and film quality. The nature of the oxides and hydrates and salts becomes apparent. Figure 4 shows the bland surface of the aluminum lithium alloy. Figure 5 shows the formation progress on these analyses.

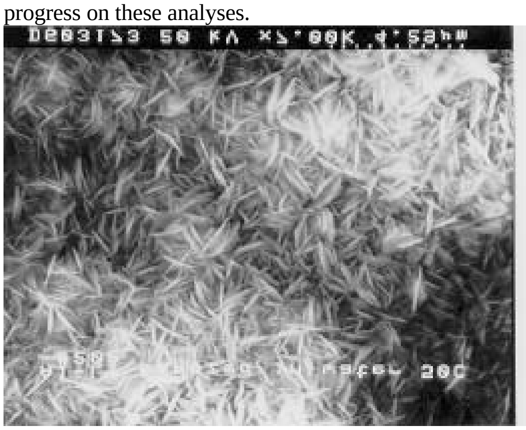

Figure 4. Scanning electron micrograph of the bland surface of the aluminum lithium alloy.

PAINT VEHICLES

The next phase of this work was to incorporate the pigments into paint vehicles. The scope of such a project was very broad and it was necessary to try a few vehicles and select one which satisfied the overall goal: which was to formulate a paint which was essentially non-polluting and which would protect aluminum from ocean water. Latex, epoxy, solvent cast, and inorganic vehicles were considered. The selected was the inorganic

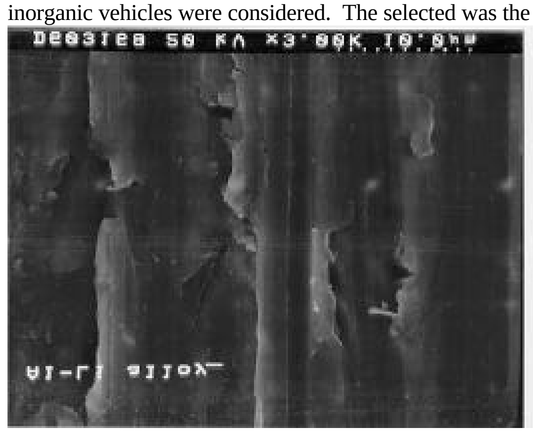

Figure 5. Scanning electron micrograph of the oxidized

lithium silicate "Lithsil-6" of FMC Corporation. It is water based and commercially available. It becomes water insoluble and it has good adhesion to metal after cure and drying. It resists heat and ultraviolet and is relatively inexpensive.

The solutions are relatively non-toxic, but they are alkaline.

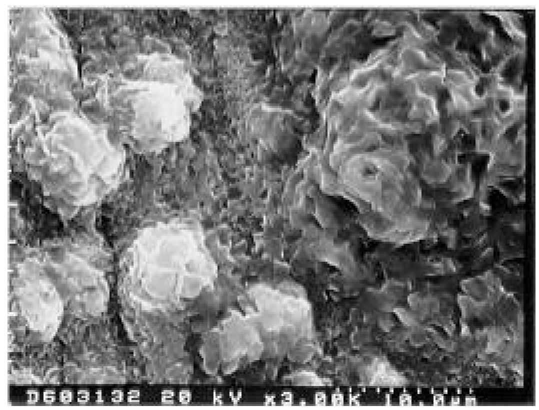

Figure 6. Scanning electron micrograph of theoxide formation following the 350C

When aluminum lithium powder is used as a pigment, the coating is light in weight. Zinc filled coatings such as Carboline's[4] inorganic zinc primer are recommended for steel and under some circumstances other metals. The success of these coatings is predicated on galvanic protection, but the zinc is less electronegative than most aluminum alloys. Lithium is the most electronegative metal and can protect aluminum, but the reactivity limits the use of the pure metal.

The aluminum lithium alloy is heated to drive the lithium to or near the surface. The surface lithium, which is heated under an argon blanket, is metallic but the oxides, hydroxides, and salts form rapidly on the surface. The heated powder reacts rapidly if it is immersed in water.

However, the lithium which has migrated toward the surface but not on the surface is available for galvanic protection. The surface lithium is available for salt formation and passivation. The lithium silicate generates the glass vehicle and alkaline lithium oxides or salts, much of which can be washed from the surface.

The Carboline base material with zinc and aluminum pigments was compared to the lithium silicate base.

The constituent range for the lithium silicate paint varied, but generally had the following formula:

Lithsil-6	1.0	parts
MICA	0.1	parts
Al-Lithium Powder	0.9	parts
Lithium Molybdate	0.005	parts

To provide a comparison, the Carboline product CarboZinc^{R} 11 represented the standard.

The latex, epoxy and solvent based vehicles were compatible, but the inorganic material seemed to offer the "cleanest" system. Since the scope of this project was to demonstrate the feasibility of a minimum polluting system and a corrosion resisting pigment to replace chromium, it was decided that the inorganic was readily formulated into an acceptable product.

Three types of aluminum Q-panels and one kind of steel panel were used for pigment tests. They were Al 6061, Al 5052, Al 3003, and cold roll steel panels. Seven groups of samples were tested that involved different formulated pigments and various treating conditions. "Lithsil-6" was used as the main vehicle of pigment. The other additives included aluminum-lithium powder, MICA, lithium molybdate, sodium borate, and zinc powder.

RESULTS

The treated panels were sent to the independent testing laboratory KTA Tater per ASTM-B117 salt spray for 168 hours. After 168 hours of salt fog exposure, the panels were evaluated, and the results are in the following paragraph. The panels were evaluated for face rust in accordance with ASTM D-610, blistering in accordance with ASTM D-714, and undercutting in accordance with ASTM D-1654. Face rust ranges from a rating of 10, corresponding to no rust, to a rating of 0, corresponding to 50% or more rust (Figure 7).

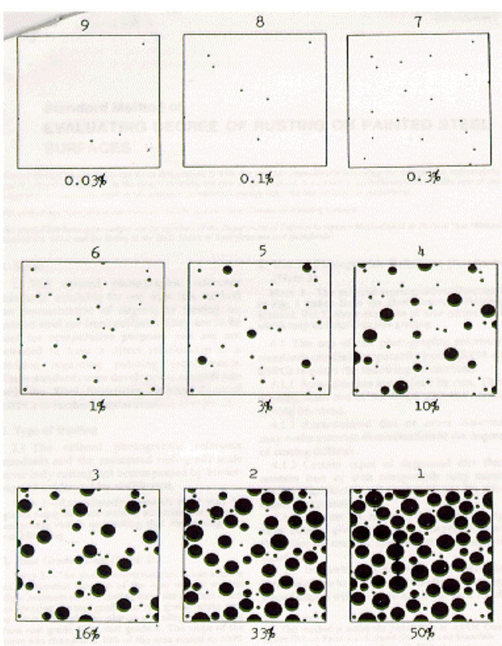

Figure 7. Examples of Area Percentages (ASTM D-610)

The results of the tests at KTA Tater confirmed the effective corrosion protection. Although the steel panels corroded seriously, the aluminum panels only had a few pits in the panels as evidenced by the white powder on the surface. The scribes which exposed bare aluminum did not corrode or undercut. No blisters on the coating were discovered. Closer inspection showed the pits were caused by lumps of pigment. The pigment which was preheated and screened had no corrosion. The top coated primer had no corrosion. The large unfiltered particles caused a circumstance of pitting corrosion which was reduced by the lithium molybdate passivator, but could be eliminated entirely by screening the lumps out prior to painting.

The mechanism of corrosion protection appears to be a combination of galvanic action by the lithium and passivation by the reaction products. The inhibitor was a complete success on aluminum. In the case of the four steel panels, the galvanic action probably inhibited corrosion but the reaction products promoted corrosion on the cold rolled steel. The technique of corrosion protection by nanostructural inhibitors is still possible, but the sacrificing pigment must not generate a compound which promotes corrosion. Lithium does not function on steel as it does on aluminum.

SUMMARY

The lithium salts passivate aluminum. They can be some viable substitutes for chromium in corrosion preventive systems. They can be used in small quantities as a pigment substitute. The aluminum-lithium provides a base for minimal amounts of corrosion inhibitors as nanostructural cores or bases of other systems.

These corrosion inhibitors can be used in other vehicles and may be used as latexes, epoxies, or solvent based coatings. This work remains to be done.

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IPPD - The Concurrent Approach To Integrating Ship Design, Construction And Operation

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ABSTRACT

This concept of concurrent engineering is a philosophy widely accepted as the correct approach to considering all disciplines in the course of a design. The methods that are used to solicit and incorporate the input are not so widely accepted. Integrated Product and Process Development (IPPD) is a technique that has been successfully applied to the Engine Room Arrangement Modeling (ERAM) project.

The paper addresses the experience of the ERAM team, which is an element of the US Navy s Mid-Term Sealift Ship Technology Development Program and will focus on issues that may be experienced in a US shipyard environment when applying IPPD. The IPPD process will be discussed from two perspectives. First the team formation, training and operation will be addressed. The team issues include such elements as team formation, requirements for collocation, project pre-planning, team training, team member development, integration of new team members, maintaining team work including peer review, establishment of norms and consensus building. In general, issues differing from current practices will be addressed. Next, the application of the approach to ship design while considering cradle to grave costs will be addressed from a technical standpoint. The technical approach will provide a general outline of the steps followed in developing the engine room arrangement models, using the IPPD approach. This outline reflects both the initial development and the evolution over several engine room designs. The conclusion of the paper will define what steps the ERAM team recommends US shipbuilders should implement in adopting the IPPD process.

NOMENCLATURE

AutoCAD®

AutoCAD is a general purpose Computer-Aided Design/Drafting design package for computers.

COMPUTER AIDED DESIGN (CAD)

Computer aided design is the use of computers to aid system engineers and designers in the design of the end product.

COMPUTER AIDED DESIGN/COMPUTER AIDED MANUFACTURING (CAD/CAM)

The process of creating a direct link between the design developed on the computer to the machine manufacturing the product.

CONCURRENT ENGINEERING (CE)

Concurrent Engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. This approach drives the designers to consider all elements of the product life cycle from conception through eventual disposal. (1)

INTEGRATED PRODUCT AND PROCESS DEVELOPMENT (IPPD)

The Integrated Product/Process Development technique proposes using TEAM involvement and TEAM 'ownership' of the development process for a given product. Fundamental concepts underlying this technique include a strong emphasis on customer satisfaction compared to the more conventional approaches, and the use of multi-functional teams. The TEAM is guided by a Steering Committee composed of upper level management who are 'champions' of the project. (2)

STRATEGIC DESIGN METHOD (SDM)

The Strategic Design Method is based on the concept of IPPD, with the multi-functional members of a design team empowered to address the total business product strategy. Using SDM, a road map is developed to provide team members with a route through the Strategic Design Processes. A key element of SDM is that metrics are used to access the direction

the team is headed and adjust the focus of the team's activities as necessary. Although metrics would appear to be a simple process, the development and application will be one of the team's biggest challenges. (3)

QUALITY FUNCTIONAL DEPLOYMENT (QFD)

QFD is a tool for formulating strategic plans of action by consolidating the inputs of numerous participants. These participants, or stakeholders, should represent a broad variety of perspectives on the subject being planned, to assure that all viewpoints are considered. The tool provides a way to impose discipline on brainstorming sessions which can otherwise tend to lose direction and focus. (2)

INTRODUCTION

This paper describes the Integrated Product/Process Design (IPPD) processes developed by the Engine Room Arrangement Modeling (ERAM) Team under a project initiated by NAVSEA under the Midterm SEALIFT Program. The objective of the project was to identify a specific set of design processes, using IPPD technique, which would lead to cost and schedule improvements for engine room design and construction over traditional shipyard practices. The team was guided by a Steering Committee consisting of representatives from academia, three shipyards, two ship owners, a design agent and NAVSEA. Guidance was provided via the 'ERAM Requirements Document' which contained the following 'Vision Statement':

> A customer-focused process that enables the U.S. shipbuilding industry to design and build engine rooms which promote internationally competitive commercial ships.

This vision statement was accompanied by seven (7) objectives.

1. Provide a forum for U. S. shipbuilders to present views and needs for product and process design.
2. Within 12 months develop a process for marine industry use to design internationally competitive commercials ships.
3. Within 24 months demonstrate the process by designing four (4) world class engine room arrangements.
4. Achieve customer-focus and buy-in of product design (4 Engine Room Arrangements).
5. Achieve U. S. shipbuilding industry-focus and buy-in of the design process.
6. Establish baseline commercial ship engine room designs for evaluation of future government initiated changes.
7. Document both the product and process design with rationale for use and future refinement by other users.

The initial set of design processes were identified during the design of a Sealift ship engine room fitted with a slow-speed diesel engine power plant. These processes were then applied to a medium-speed diesel and an additional slow speed diesel plant design, and were continuously improved as the project's participants gained more experience.

To arrive at the recommended design processes, a course of action was set at the beginning of the project to identify baseline processes. Careful monitoring was continually performed to identify both positive and negative aspects of these baseline processes. Based on the lessons learned in executing each iteration, the processes were refined.

The lessons learned include lessons related to IPPD, SDM, and QFD techniques which were applied throughout this project. The resulting refinements were based on careful observation of which aspects were found to be effective, and which were found to be ineffective.

The IPPD processes are divided into six major topics:

- Team Selection
- Team Development
- Design Product Development
- Product Model Development
- Build Strategy Development
- Metrics Development

The design process described herein assumes that; the shipyard designers are relatively inexperienced in the design and arrangement of commercial ship engine rooms; available baseline or reference ships are out-dated, non-competitive or require extensive modification to suit current requirements; and few or no commercial standards are in place. As experience is gained and more suitable baseline ships become available, many of the recommended design process steps may be abbreviated or converted to shipyard standards which do not have to be redeveloped for each successive contract.

IPPD TEAM SELECTION AND DEVELOPMENT

This section provides a detailed description of the recommended approach for assembling and training an IPPD team. The start-up of any project requires a 'champion' to sell the project to company management. Once the project has been endorsed the following steps in selecting the team members are recommended.

Team Selection Process Development

The first and most important step is to establish a clear task definition, Figure 1, prior to team selection so that the team can be customized to the task. (4)

A well defined task is one with a clear vision statement, a clear set of objectives and a clearly defined set of strategies. These elements are essential to a project's success.

As a first step in clearly defining the task, the Quality Function Deployment (QFD) tool (Reference 2) should be utilized to identify the 8 or 10 top

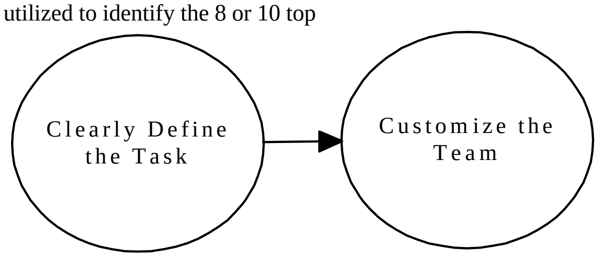

Figure 1. Customizing the Team to the Task

customer required characteristics for the product. These 8 or 10

characteristics should then be used to
identify the skills required. See Figure 2 for the recommended procedure for identifying team member skill requirements. Other synergistic methods, such as, early customer involvement in determining customer requirements can also be used. It is strongly recommended that individual opinion approaches to identifying skill requirements be avoided.

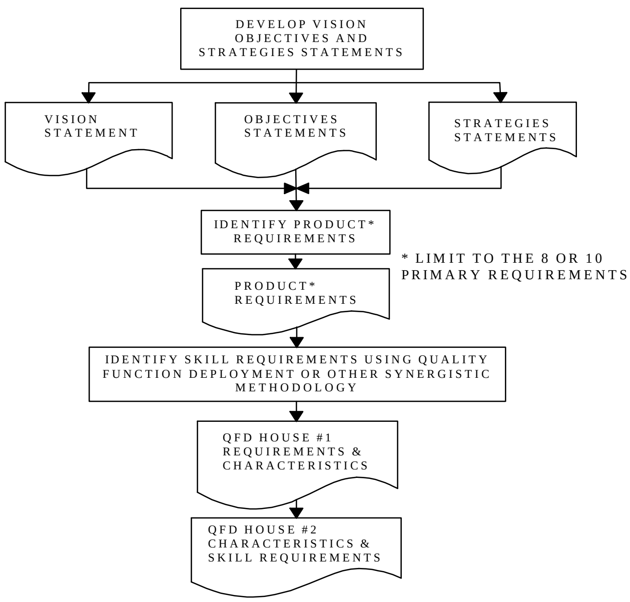

Figure 2. Identify Team Member Skills Process Flowchart

The selection of team members, in many ways, is similar to normal hiring procedures in that skill requirements vs. cost must be a factor. It is essential that the required skills to provide the characteristics identified in Figure 2 be provided. Hence, it may be necessary to acquire support sources other than those directly available sources within the company. Not all team members will be required full time. It is recommended that the core team/resource team concept be adopted. The part time resource team personnel should participate fully in the team training and development process. See Figure 3 for the recommended selection process.

The following is the recommended team composition for an engine room conceptual design team:

Core Team *Permanently At Design Site*

- Team Leader
- Design Engineers - 8
  1. Hull/Structural - 1
  2. Piping System - 3
  3. Machinery Engineer - 1
  4. Outfitting/HVAC/Arrangements - 1
  5. Electrical (Control & Monitoring) - 1
  6. Production (T & E/ Construction/Build Strategy) - 1
- Computer-aided Design Team Leader - 1*

Resource Team *Permanently At Design Site*

- Computer-aided Designers (Including Team Leader) - 8
- (One Designer skilled to support each

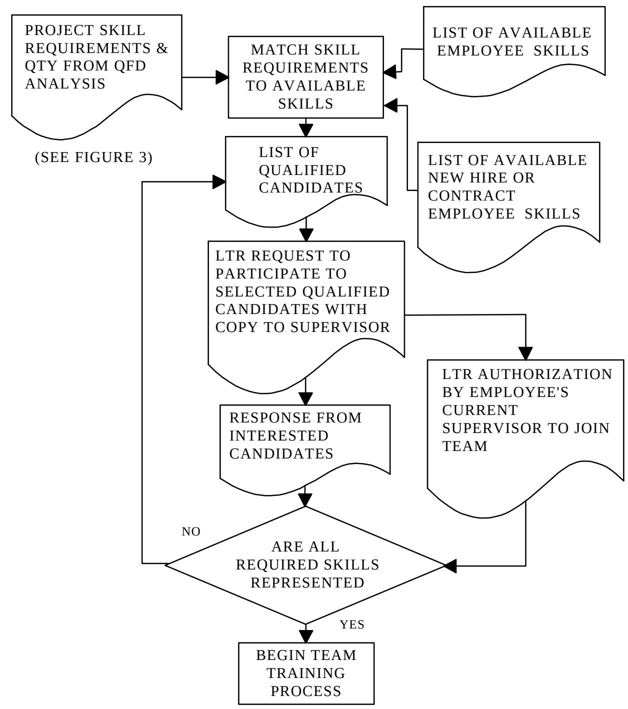

Figure 3. Team Selection Process Flowchart

Design Engineer)

- Design Site Administrative Support - 1

Resource Team *Periodically At Design Site (2 - 3 Weeks in Duration)*

- Propulsion Equipment Vendor Applications Engineer - 1
  (Diesel, Reduction Gear, and Propeller Representative as needed)
- Ship Owner/Operator Representative - 1

* This position may be eliminated if the Core team has sufficient computer knowledge.

Design Project Teambuilding/Training Program

A summary of the teambuilding approach is presented as Figure 4. The steps are further elaborated in the text following.
Step 1 - Design team developments should start with an orientation kick-off meeting which outlines the goals and objectives of the selected design team. These goals and

objectives of the selected design team. These goals and objectives should be developed by a Management team such as a Steering Committee. All goals and objectives should have the approval and buy-in of top management before they are presented to the design team. It is essential to have all goals and objectives developed before the training of the team begins, this promotes a better understanding of the overall project from the start.

Step 2 - Cross functional team training (5) should consist of the following:

- Preliminary Team Building Activity
- Skills and Techniques of a team Player
- Success Strategies for Cross-Functional Teams:
- Concerns and Questions Meeting the Steering Committee Outline
- Cross-Functional Team Simulation
- Review of Key Success Factors
- Developing Operating Agreements for Design Team
- Tools and Techniques for Effective Team Meetings
- Stages of Team Performance: Forming, Storming, Norming and Performing (2)
- Team Environment (Collocation)

Step 3 - Team meeting training should be provided to the entire design team which should include formal training in the following skills:

- Facilitation (controlling a meeting),
- Process Observation (reviewing the process followed and presenting positive and negative aspects of the meeting, referred to as plus and deltas) and
- Scribing (the art of taking notes on flip charts or view graphs).

Everyone on the team must understand the importance of these three factors in any meeting and be able to conduct themselves in a manner which will allow all three skills to be practiced most efficiently.

Step 4 - Practice working as a team by applying the training concepts in a team setting.. It is recommended that the core team be collocated adjacent to a large dedicated meeting room where information/development data can be posted for the team's constant review. Excellant resources for team related problem solving are references (6) and (7). It is recommended that references (8) through (15) be required reading for this step.

Step 5 - IPPD training should consist of the following.

- Team Management Practices
- Team Planning Session: Norms, Mission, Organization
- Communication Planning
- Team Planning Session: Communication Plan
- Customer Focus
- Team Planning Session: Customer
- Requirements
- Project Management for IPPD: Core Team and Support Ring
- Team Planning Session: Evaluation of Architecture
- Team Planning Session: Task Plan and Subteam Assignment
- Performance-Based Measurement (Metrics)
- Partnership Agreement, Next Steps Team Planning Session

At this point of team development it is imperative that the team develop a team dynamics measurement tool. This tool should be designed to help the team improve their performance in the areas that are considered important to the team development process. The focus of this tool is to build on successes and to identify and correct specific problems based on the team's norms.

Step 6 - Practice as a team by developing the following major subteams.

- Core Team
- Communication
- Team Agreements
- Training
- Resource Management
- Technology Management
- Vendor Furnished Information (VFI)

Step 7 - Strategic Design method training (4) must consist of the following.

- Why Concurrent Engineering Works
- Process-Based Design: A Concurrent Engineering Methodology

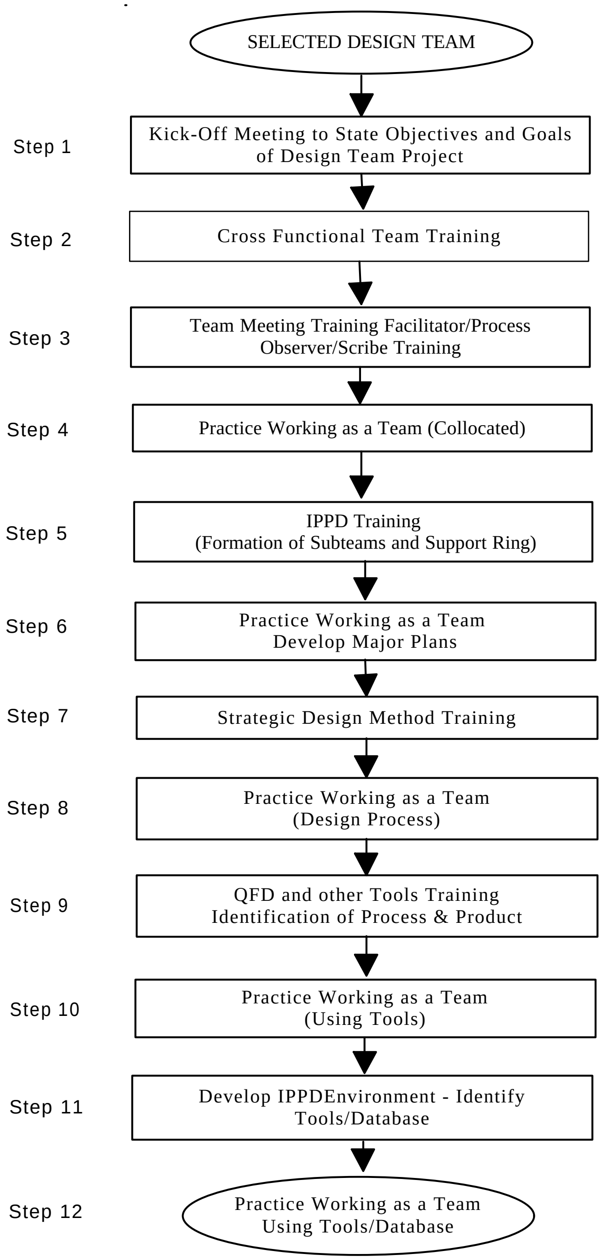

Figure 4. Teambuilding/Training Process Flowchart

- The Six Concurrent Engineering Skills
  - How to Analyze Product Requirements
  - How to Build A Winning Strategy
  - How to Create Competitive Designs
  - How to Rate Designs
  - How to Reduce Design Cycle Time
  - How to Build Team Success
- Best Practices of Winning Teams
- Case Studies
- The Teamwork Approach to Product Development
- Guidelines for Concurrent Product Development

All of the above are necessary skills the team must learn to successfully complete the concurrent engineering design process. This concurrent engineering process should bring the following to the team.

- Put Process and Product in Perspective
- Emphasis on Problem Seeking
- Excellent first step in design process
- Systematic approach to any design process

Step 8 - The team as a team, or several smaller teams, must practice the necessary skills on a small design project to gain experience in these methods. After several iterations of the Strategic Design road map; the design team should be able to develop a Strategic Design Brief in a three day period. First time development is best achieved with the assistance of a professional coach. (4) The intent of this Strategic Design Brief is to outline the design team's direction in developing the project, and gain management's (Steering Committee) buy-in.
Step 9 - The team must be trained in the use of design tools such as QFD. This tool is designed to focus on customer requirements, product and process characteristics and tasks. QFD is a fairly complicated process and should be taught by a qualified professional instructor.(5) This tool can be used to identify all process and product tasks needed to complete a detailed design process. The effort should focus on the critical points e.g. the team has to go deep into the build strategy and just superficially into sewage and drainage system concepts.
Step 10 - The team must practice using design tools. It is suggested the team develop QFD subteams to develop process and product houses. This exercise should produce a complete set of design tasks.
Step 11 - Establish a subteam, including computer support experts, to identify, implement, and support the computer applications required for all process and product activities for team members and external resources (Steering Committee, shipyards, owners, vendors etc.). The subteam must use advanced communication software between external resources to keep the record and maximize cooperation with external resources.
Step 12 - The computer applications subteam should develop "Computer Applications User's Guide" and a training program to allow the implementation without interruption of team member's daily project activities. An adequate amount of time must be provided for every team member to practice using these tools.

It is suggested that a professional IPPD/Concurrent Engineering coach be present with the team throughout the development of the team to give guidance and support in the development of individual teaming skills.

The team should devote as much time as possible to understanding the objectives of the training, especially team building. This will create a greater feeling of comfort with the IPPD process and tools.

The design team must understand that there is no "perfect ship", but just a full integration between shipbuilders and shipowners, which allows for sacrifice of some aspects to increase others, depending on priorities of both sides to reach an

agreement. Shipbuilders and shipowners should be partners, not rivals.

Pitfalls

The following pitfalls must be eliminated to have a successful team environment.

- Management expecting product output during the three to six month team development period.
- External management allowing team members to bring team problems outside the team for resolution.
- Not empowering the team to remove ineffective team members.

ENGINE ROOM DESIGN PRODUCT DEVELOPMENT

This section provides a description of the recommended approach for the design of an engine room.

Product QFD Development Process

This section is written assuming the reader has a basic knowledge of QFD, QFD houses, house rotation, and QFD house interaction scoring and weighting. See Reference (5) for detailed information on QFD.

By having a product sub-team composed of customers, operators, engineers, designers, production representatives who know how to use the QFD tool, a Product QFD House can be developed using the process described in Figure 5. Working groups for QFD houses should be no larger than eight and the participants should be committed to completing the task. Individuals should refrain from coming and going at will as continuity is not maintained. During this session the customer requirements are identified and prioritized by the customer and the characteristics of the product are identified by the customer and the

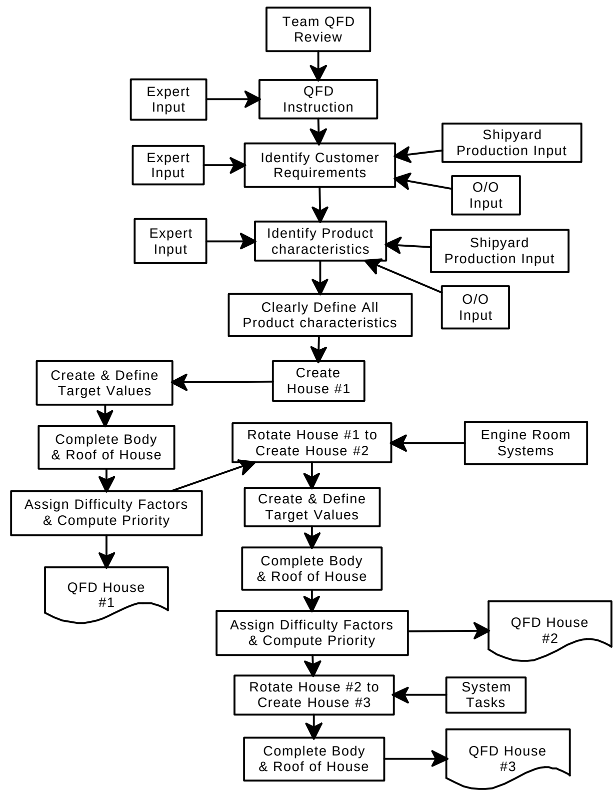

Figure 5. Product QFD/Task Development Process Flowchart

QFD subteam. It is very important to get customer input during the analysis to help answer any questions or uncertainties that arise regarding owner requirements.

Prioritization of the product characteristics is accomplished by identifying the interactions between the requirements and the characteristics and the level of importance of each interaction. All items on the house axes need to be clearly defined and agreed upon prior to doing the QFD analysis. This will help in resolving possible disputes and misunderstandings later on in the analysis. Participants should endeavor to keep the number of items on any single axis as low as possible. The addition of a single item requires a significant amount of time. Items may be deleted or combined to simplify the QFD house or the house may be split into smaller houses. The systems to be included are brainstormed by the team and listed on the horizontal axis. Interactions between the systems and product characteristics are then rated and prioritized.

QFD Completion

The QFD houses are reevaluated based on the Strategic Design Brief results to ensure that the focus of the QFD houses is in line with the SDB. QFD House 3 is developed to identify the technical design tasks required to meet the requirements and to prioritize those tasks.

A complete list of subtasks is then created based on the third QFD House. This is accomplished by comparing each of the

systems to the technical design tasks. For example, Table 1 is an excerpt from a fuel (purification) system comparison.

System	Technical Design Task	Design Subtasks
Fuel (Purification)	ER Arrangement	Locate all equipment within the engine room
	Master Equipment List (MEL)	Develop MEL for fuel purification equipment
	System Diagram	Develop System Diagram for fuel oil purification system

Table 1 Fuel Purification System Design Tasks

Each engineer is then assigned cognizance over one or more engine room systems and one or more technical design tasks. System cognizance typically requires developing calculations, diagrams, specifications, and selecting equipment for that system. Task cognizance requires completion of the administrative jobs associated with each task. These might include developing drawing formats, numbering schemes, and a list of standard symbols. The assignments are made based on interviews and discussions conducted with each team member to determine their capabilities and preferences while attempting to maintain a level work load. A typical member's work load might be Table II.

Changes to the tasking may occur as some individuals pass portions of their system responsibilities to others. Many of the task responsibilities may prove to be far too large to be accomplished by a single individual so subteams must be created to further reduce the time requirements for the participants.

Systems	Design Tasks
High Temperature Central	System Diagrams
Freshwater Cooling System	Component List
Low Temperature Central	System Diagrams
Freshwater Cooling System	Component List
Potable/Drinking Water	System Diagrams
	Component List
Steam	System Diagrams
	Component List
Fire (Non-seawater)	System Diagrams
	Component List

Table II Typical Team Member s Work Load

Project Schedule Development

The schedule development should be based on the QFD product house. The resulting task list should be as detailed as possible, presenting every task and sub-tasks for every system.

Project and task completion dates, vacations and holidays, as well as the availability of core team and resource team personnel should be known.

The phases of the design development should be defined with at least the following three phases identified:

- Conceptual Phase (Phase 1), where the concepts are established and settled, based on the main requirements, kept as short as possible;
- Development Phase (Phase 2), where the design is developed based on the definitions of the first phase and where the main equipment and associated technical data should be carried out; and
- Refinement phase (Phase 3), where the design incorporates additional internal improvements and refinements as well as external comments.

The duration of each design phase is based on the available baseline design documentation, and level of skill and experience of the participants. The schedule should include a time tolerance.

The schedule should be available to all team members for tracking tasks and early identification of the areas requiring assistance.

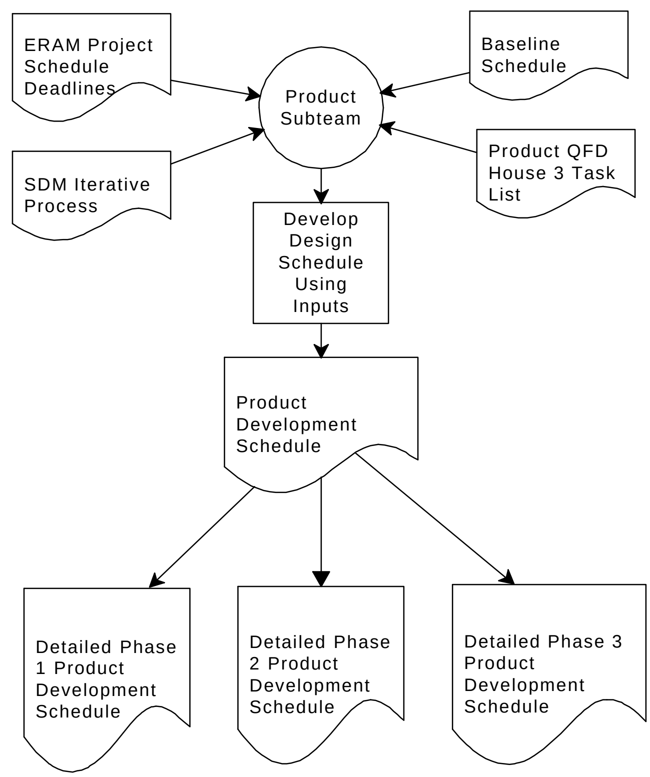

Figure 6. Product Schedule Development Flowchart

3-D PRODUCT MODEL DATA DEVELOPMENT PROCESS

In order for the product model to be integrated into the design, construction, and business practices employed at the shipyard, it must have sufficient detail to be useful in making design decisions. The type of data and level of detail available in the product model needs to be correlated to the various stages

in the design process. The product model development scenario is based on the following assumptions:

- During the conceptual design stage, the product model is extremely dynamic but the level of detail is low.
- Early stage design is concentrated on system diagrams.
- During detail design, the product model is less dynamic, but the level of detail increases greatly, and configuration management becomes complicated.
- During the construction phase, configuration management is the most difficult due to the introduction of the many dissimilar systems required to support the manufacturing processes.
- The majority of engineers/designers do not have access to the CAD system.
- Many engineers/designers supply data to one CAD technician.

The product model development process can be summarized as follows.

- Define library parts
- Hull Definition
- Locate Decks/Major Bulkheads
- Define Major Structure
- Locate Major Equipment
- Locate Tanks
- Arrange remaining equipment
- Define Deck and Bulkhead structure
- Define distributed systems lanes
- Locate major piping
- Optimize equipment location
- Organize equipment into units
- Structural details
- Optimize unit location
- Define foundations
- Arrange minor piping
- Optimize distributive systems

In addition, for the product model to be useful it must support the development of the documentation required for periodic design reviews and the development of the traditional drawings at the completion of the design.

Software Selection

Software has to be obtained to create and access the product model data. There are no commercial off the shelf systems which can adequately support ship design and construction within a specific business context without being customized. The development effort required to integrate the software, ease of use, and reliability, should be a significant consideration in the selection process.

One of the most important steps in the selection of commercial software is the evaluation. Software must be evaluated in the context it will be used in the shipyard. The evaluation should include at least a prototype implementation in which interfaces are developed to all major shipyard processes. The implementation should be phased, based upon the requirements of existing and planned projects.

Personnel Selection and Training

An ideal CAD user is an experienced designer and engineer with an expert understanding of the application software. The user needs to be trained not only in the use of the system, but must be familiar with the design and construction processes as well. It is very important to integrate actual examples of shipyard processes into the training process in order to reinforce the theory as well as to prepare the user for actual tasks. The CAD team should consist of a core of application experts who can provide some guidance in addition to performing their own tasks. Initially, inexperienced users should develop library parts and assist the application experts. As they gain experience they will require less guidance and can be assigned more difficult tasks. Cross training should be performed where practical in order to provide awareness of the overall product model as well as to develop a reserve of users to accommodate a shifting workload.

Other resources required to support product model development include system support, application programming, and library part development. The system support role does not really require knowledge or experience with the application software. The application programmers should have a great deal of knowledge and experience with the software. Experience and knowledge of the ship design and construction processes is highly desirable. Library part modelers should have an expert understanding of the CAD application and an understanding of the level of detail required to represent a component. Experience and knowledge of the ship design and construction process is not necessary. Notice the level of experience for the application programmers and library part modelers are opposite of the ideal CAD user. Additional training is required for non CAD users who require access to the product model. This training should consist of visualization and redlining techniques in order to review and comment on the work in progress. Application of IPPD process by the CAD sub team is critical due to the close interaction between all the roles involved in product model development.

Product Model Preparation

Before a product model can be developed, an infrastructure must exist which includes configuration management, procedures, components and commodity items, and system support. The process of developing the product model requires the identification and modeling of equipment, outfit, and furnishings before these items can be inserted into the model. The product model is highly dependent upon the availability of commodity parts such as structural steel shapes, major equipment, outfit and furnishings, valves, fittings, etc. The first ship designed using the system is generally the hardest because in addition to design and construction, the infrastructure is under development.

Library Parts and Commodity Parts

Since commercial CAD/CAM systems are used to develop

arrangements, structural, and distributed systems models it is highly desirable that this data be provided in a digital format. This data consists of the information required to represent the as-built geometric definition of the component as well as the attributes required to convey non-graphic information. The vendor files should be accessible to all CAD workstations for reviewing, printing and referencing as a "footprint" for modeling. A database should be developed which provides information about the availability of the data and the developmental status of the library parts. It is recommended that a group be established to support the product model library consisting of CAD users and personnel who can obtain and document the data required to build the equipment. The best practice is to receive the data formatted specifically for the product modeling system. This will require a partnership between the shipyard and suppliers.

Product Model Procedures

Due to the complexity and the all encompassing scope of the product model, a set of procedures and guidelines must be established to ensure that the product model will be developed in a consistent fashion. There should be a general set of guidelines which pertain across all applications as well as application specific guidelines. For example, configuration management, general model organization, product work breakdown system, and component modeling procedures will probably be the same across applications because they affect the product model globally. Value added modifications to the product model such as manufacturing data or engineering analysis data, which have a local effect between a limited number of groups, require unique procedures. The procedures need to consider not only how the product model will be used to perform a specific task, but the effects on other users as well.

Product Model Usage

In general it is best to have a single product model which can be accessed in a distributed environment by all 'electronic' design and construction processes (e.g. arrangements, distributed system layout, structural design, pipe flow analysis, structural analysis, naval architecture, plate nesting, pipe bending, etc.). This means the sophistication of the product model varies among the shipyards. The uses of the product model must be known in advance. For instance if the end product of the product model is the creation of drawings, a radically different approach will be undertaken than if the product model will be used directly to support ship construction. A process must also be developed for product model development. The definition of the product model as well as its development and implementation necessitates the involvement of all groups which will be creating as well as accessing product model data. The sequencing of access to the model must also be determined, including the output products required to facilitate communication of the information. Currently, access to the product model by others than CAD users are through annotated sketches generated from the product model. This is also the predominant methodology used for design review. Anyone who has input into the design must be trained and given access to the product model. Design reviews should be facilitated using electronic mockups.

Product Model Development

The product model can be initiated from many different sources, including existing product models, CAD drawings, and paper sketches/drawings. Also in the conceptual phases, much of the 3-D layout is unknown. The system must be able to accommodate new ideas and scanned images. The first iteration of a new design can manifest in any of the three formats. As the arrangements evolve, the CAD technician populates the product model and generates models and sketches as defined in the product model development procedures. The next step is the definition of pipe lanes. As the model becomes more mature, it becomes suitable for providing the documentation required for the design review. Once the piping lanes have been identified the distributive systems can be defined in more detail in the product model. This more complete product model would be used to optimize equipment arrangement and begin the grouping of equipment into units. As the units evolve, the foundations can be modeled, and structural details can be designed. Although product model development lags slightly behind the optima time in which data should be provided to the designer, the data can be delivered in time to have a positive influence on the design. This cycle is repeated until the design phase has been completed.

Product Model Output Products

Output products are used to provide information to downstream processes and interim documentation and may be the final end products as well. For example, graphics files required by a visualization system for design reviews is an end product. Work packages generated from the product model in a paper format may be required on the waterfront by the trades. Final drawings are still a requirement in most applications. In-process output products include finite element models, equipment lists, and numerical control instructions. Sketches generated from the model may be required to convey information to the system engineer who does not have product model access.

- Design Documents (released continuously)
  - Sketches
  - Reports
  - Visualization files (shaded images, hidden line)
  - Manually created 2-D Schematics (provided upon request)
- Design Review Documentation (released periodically)
  - Annotated drawings required to communicate system diagrams and arrangements
- Visualization files (Documentation (released semi-weekly)
  - Product Model Review files downloaded
- Product model neutral databases (as requested)

This data will initially be provided in the format as defined in digital data exchange procedures. Long term plans are to

provide the data in Standard Technical Exchange Program (STEP) format conforming to the ship design and construction application protocols:

- Arrangement;
- Structure;
- Distributed systems; and
- Library parts.

- Final Drawings (end of project)
  This requires major rework of the latest design documentation. These drawings shall be developed explicitly from the product model and annotation added manually as required. Editing of line style shall be performed as required. This process is developed after the product model has been completed, and will be non-associative to the product model.
  - Paper drawings
  - Raster images
  - Drawing Interchange File (DXF) files (2-D)
  - Initial Graphics Exchange Specification (IGES) files (2-D)

Hierarchy for the Acquisition of Commodity and Library Part Data

1. Provide digital data in native format in conformance to product modeling library development guidelines. Basically, this data consists of geometry for the various representations of the part (e.g. detail, 2-D symbolic, envelope, etc.) and the non-graphic attributes for the required level of intelligence.
2. Provide the geometry and attributes using the appropriate National Shipbuilding Research Program (NSRP) specification for the definition of STEP application protocol for shipbuilding.
3. Provide the geometry and attributes using the Initial Graphics Exchange Specification Version 5.2 or greater. Multiple formats are available within IGES to represent this data. The preferred method would be to use CSG and Brep solids to represent the geometry and the attribute table and instance entity to represent attributes. In the event the preprocessor is not robust enough to handle solids, then surfaces or wireframe geometry would be used. If the preprocessor is not robust enough to handle the attribute table and instance entities then a text file would be used.
4. Provide the geometry using DXF, and the attributes using a text file. The preferred DXF geometry type would be surfaces, however wireframe is acceptable if surfaces are not available.
5. Provide the data in native format AutoCAD or Microstation.
6. A scanned image of the applicable technical publication describing the component would be used and the attribute data would be provided in a text file. Regardless of the methodology used to represent the vendor data, it is highly desirable for a raster image of the technical documentation be provided.
7. Provide sufficient technical documentation to develop a CAD model of the exterior of the component, including the location and orientations of connections (structural, fluid, electrical).

SHIP S SYSTEMS DEVELOPMENT

The System Development Process is shown on the flowchart of Figure 7. Development of systems starts when the systems are identified in the QFD product house and ranked according to how difficult they are to implement and how they interact with other systems. After the systems are identified, the product subteam assigns the systems to individual core team engineers. System assignment is based on the time required to develop each system and core team knowledge. At this point, each engineer develops his system concurrently with all of the other systems. System concepts can be refined throughout the conceptual and development phases along with trade-off studies, equipment selection, owner/operator input, build strategy and during the level of unitization defined during Phase 2.

The core team defines, selects or adopts a proven baseline for all systems before the start of a design. This will pay off downstream with regard to minimizing the time spent in discussion within the team about content. It also supports the team by reducing the ‘blank sheet of start-up time. Systems such as the following are to be considered.

- Exhaust Gas
- HVAC
- Sounding/Venting & Overflow
- Structure
- Fuel Oil Supply and Purification
- Sea water
- Propulsion
- etc.

Systems specifications need to be defined at the start of the project. System requirements should be changed to match commercial practice on world class ships as defined by the core team and owner/operators.

Diagrams

A diagram subteam can be established early in Phase 1 to create rules and guidelines for system diagrams and to select the 2D CAD software for engineers to create the system diagrams. It is necessary to agree to use only one type of software for these diagrams. Also, a universal list of equipment symbols and valve symbols must be used to promote consistency amongst the system diagrams.

The level of detail listed on the diagrams must be agreed upon for all system oriented diagrams. This level should require clear presentation of system

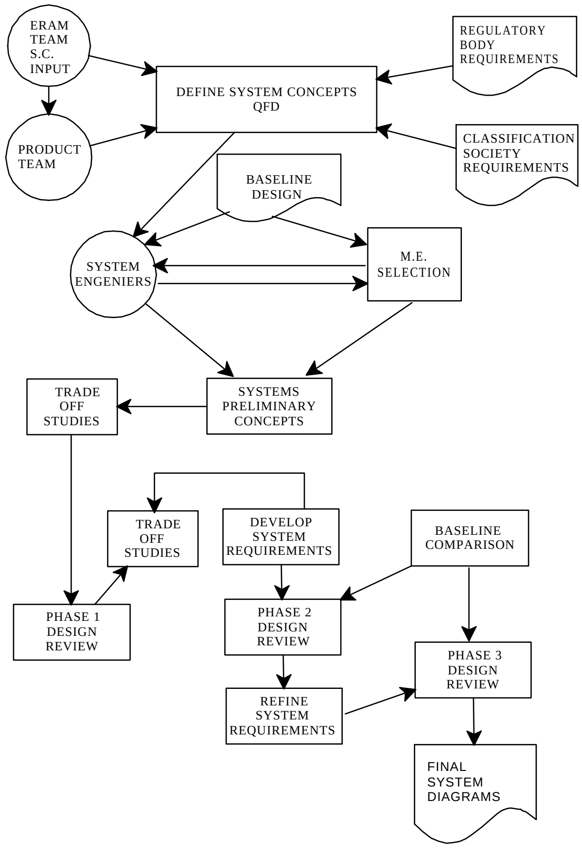

Figure 7. System Development Flowchart

function, ease of understanding, and system interaction must be identifiable with references to other diagrams where needed. The equipment on the diagrams should be positioned similar to the actual room arrangement to later simplify the unitization breakdown process.

The revision and approval process of the diagrams and drawings need to be properly defined prior to the completion of the first diagram.

Trade-Off Studies

Trade-off studies on system design philosophies and equipment selection should been done throughout Phase 1 and Phase 2. The initial system concepts can be based on the following items.

- The system concept to be commercially viable
- The baseline ship
- The eight key 'Illities' listed in the SDB
- Ship rider reports
- Owner/Operator written comments
- Core team input/evaluation

Goals for the trade-off studies are as follows:

- Create a simple, but efficient system that is commercially viable, a proven concept, easy and economical to build and operate that provides high reliability.
- Reduce in number of equipment, thereby minimizing the equipment to be maintained
- Reduce the amount of sea-water piping to reduce problems as the ship ages and the sea water piping corrodes

Equipment Selection

The equipment selection process must be defined for the project. The vendor furnished information library needs to support the equipment selection process and allow access for engineers to look for equipment and vendors. In many cases that the support from vendors takes too much time and is a constraint for the engineers and the schedule. The need for drawings and information will be a great concern for the team if the vendors are not as willing to provide information.

Project Database

A project database must be able to manage conceptual design and formation in a central manner. From this database, reports covering design information, master equipment list, parts list, list of units and blocks could be generated. Other uses included capturing data for the electric load analysis and automation and signal list. Several examples of the database content can be found in the ERAM design package.

PRELIMINARY DEVELOPMENT OF ENGINE ROOM ARRANGEMENT

This initial step of engine room arrangement involves propulsion unit identification and integration within the engine room envelope. Additional studies can be performed to specify:

- Tank top, main grating and intermediate flat levels;
- Main engine foundation;
- Height of the shaftline;
- Location of the engine room bulkheads;
- Location of the fuel oil tanks; and
- Location of stack/casing.

This development of this step is done using 2-D drawings derived from the 3-D model.

The main items of the preliminary engine room arrangement identified in the first step are presented to the team. During this discussion the main drivers for spatial relationships can be identified.

Development Of Engine Room Arrangement Options

Engine room arrangements can now be developed by individual team members or subteams to provide several options. Affinity diagrams and the "QFD" house matrix, Figure 5, are valuable tools at this stage. Concurrently a preliminary pipelane arrangement study can be performed.

These arrangements are now presented to the team with an explanation of each concept and configuration.

Selection Of One Option For The Engine Room Arrangement

For each option "plus & deltas" and "QFD" analysis are applied to validate and select the preferred option.

The preferred option selected by the team can now be optimized to further improve the arrangement and incorporate the best features from the discarded options if necessary.

ENGINE ROOM ARRANGEMENT DEVELOPMENT

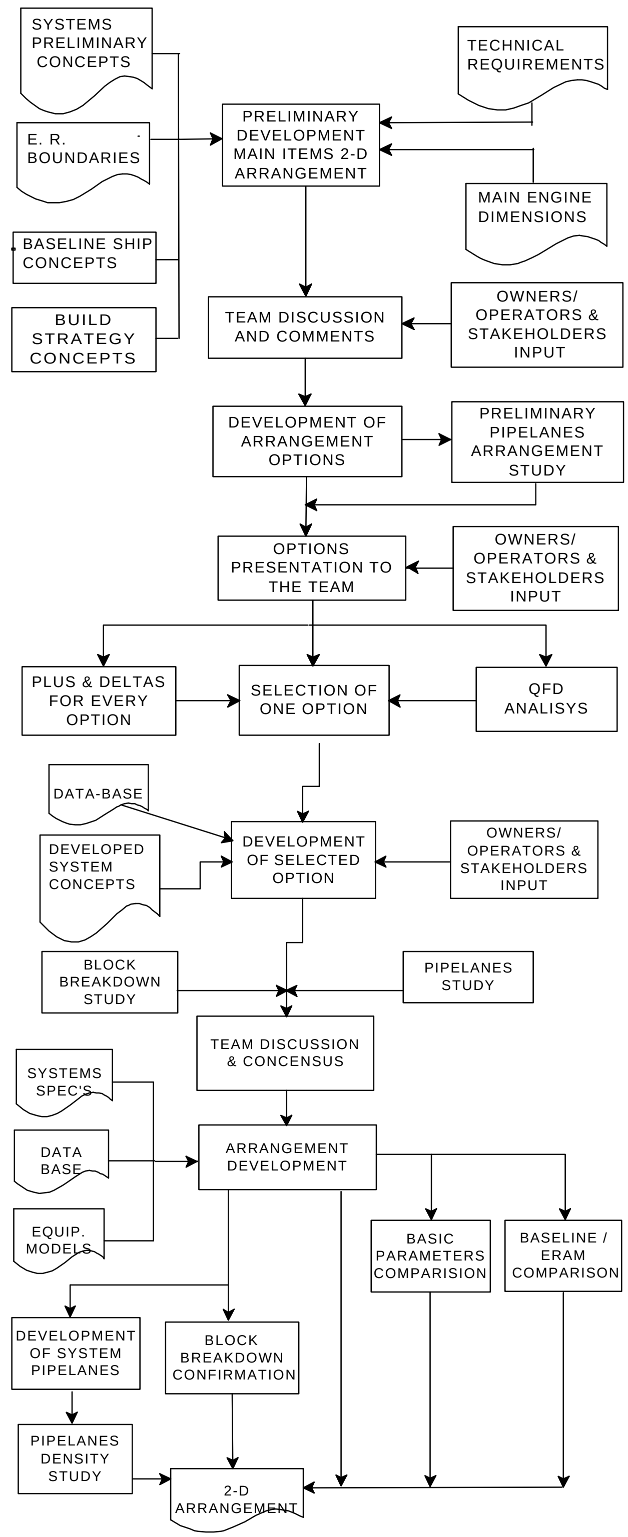

Figure 8. Engine Room Arrangement Process Flowchart

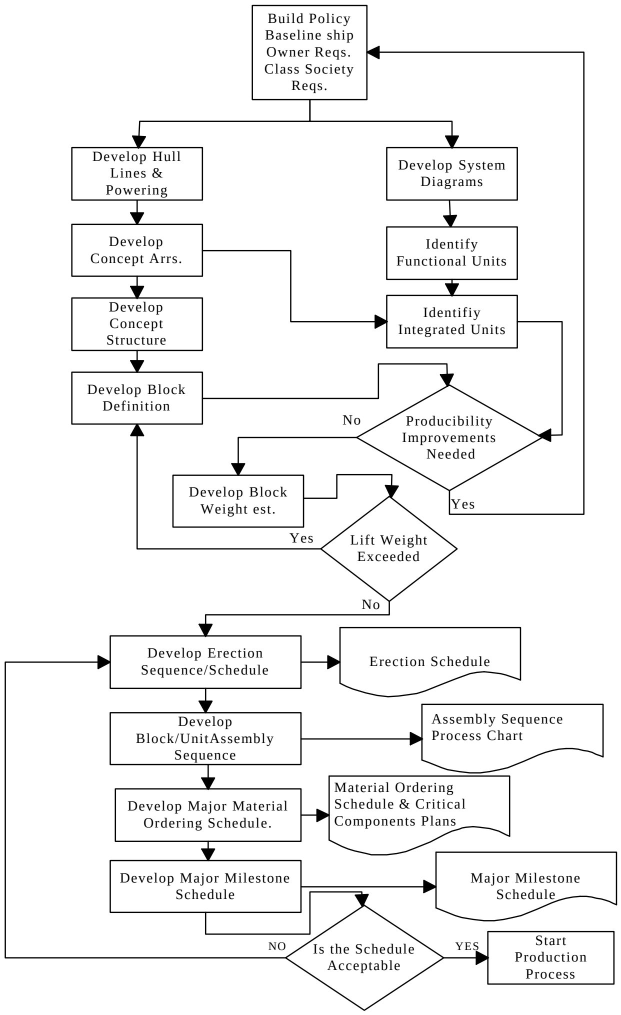

Figure 9. Build Strategy Development Flowchart

The arrangement can now be populated using the 3D model and data base. Development of system pipelanes from earlier studies can now be included in the 3D model. As the 3D model is developed detailed arrangements can be accurately produced at any time with minimal effort. Final arrangements are a feature of the completed 3D model.

BUILD STRATEGY DEVELOPMENT

Build strategy development is initiated in parallel with the engine room arrangement studies and system diagram development. See Figure 9.

This process includes initial system design steps to:

- Simplify systems;
- Combine system functions;
- Minimize number of components;
- Define intersystem relationships; and
- Define system level units

using such tools as affinity diagrams (See Figure 10), equipment association tables, networks, and analysis of system schematics.

Development of the build strategy begins with the provisional establishment of block boundaries, in accordance with the following principles

Program Considerations

Interim products must fit the characteristics of the shipyard and block breaks and erection sequences should be compatible with the production strategy developed during GBS Phase II for the total ship. The overall production strategy must support the goals of the Strategic Design Brief and the Requirements Document, including:

- Ship delivery schedule after contract award;
- Engine room cost;
- Latest feasible delivery/installation of main engine; and
- Minimum design/marketing cost and no financial commitments (e.g. for long lead material) prior to contract award.

Logic and Criteria

Favor outfitting in any tradeoff between structural and outfit production and maximize interim product size within the facility constraints. Standardize components, arrangements and interim product configurations. Other factors to consider include:

- Move work to the earliest feasible stage
- Installation

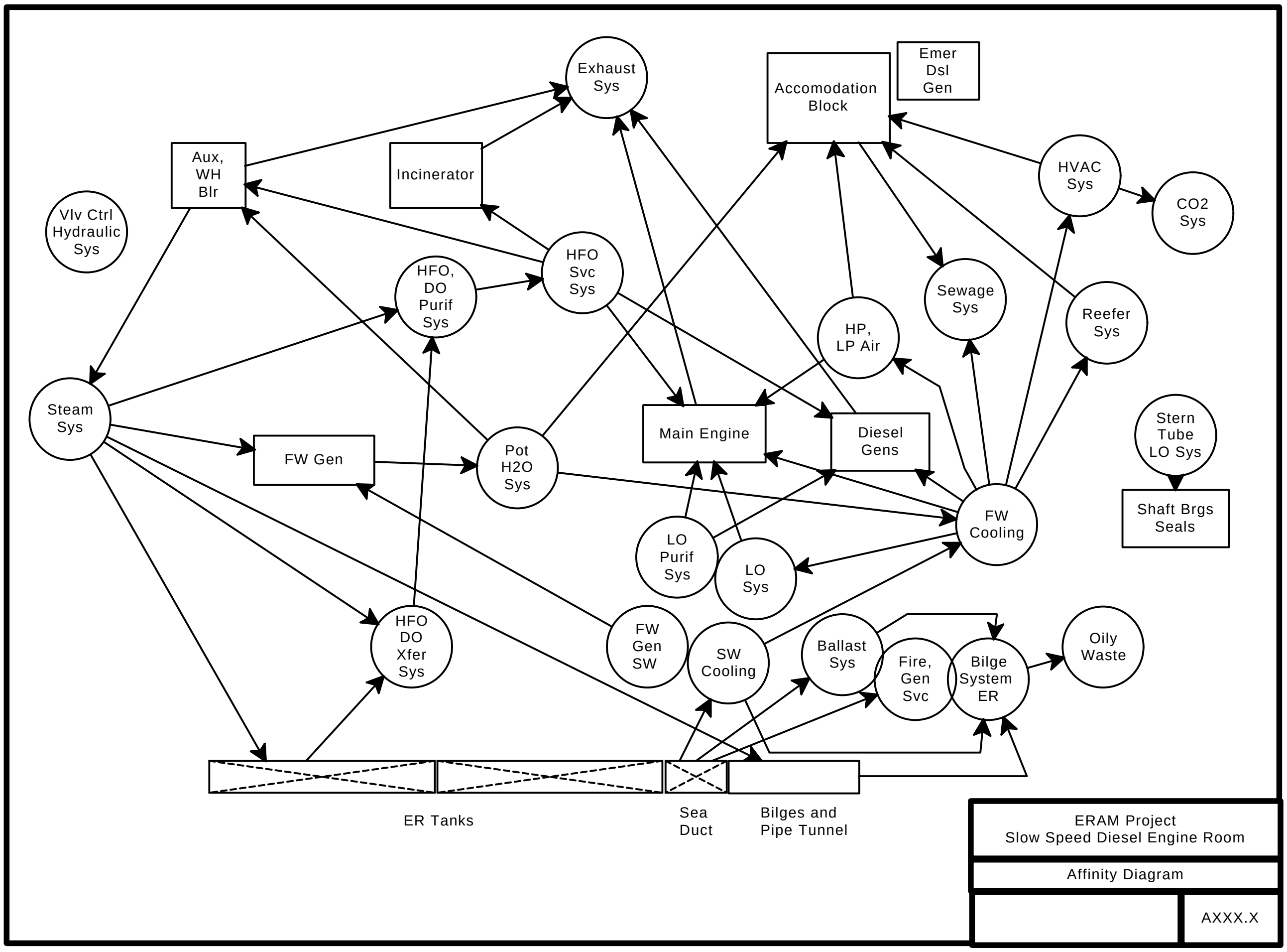

Figure 10 Engine Room Systems Affinity Diagram

- Testing;
- Minimize joint (weld) length; and
- Provide flexibility to allow for the unexpected.

Production Process and Sequence

Assemble blocks on flat surfaces (usually decks) on the assembly floor (no pylons, minimize use of pin jigs). Provide for parallel processing of interim products and install all possible components on unit Install units on-block wherever weight limits permit, otherwise on-berth and use grand blocks/units to increase the efficiency of the on-berth erection process. Maintain open access to all blocks containing outfitting, including a window for blue sky outfitting on-berth. Include the following items in the development of the build strategy.

- Minimize time between material delivery and ship delivery ("just in time")
  – Install main engine as close to launch as possible (late installation)
- Minimize time between keel and delivery
- Load hook up (free ride) material on-block
- Complete test and paint structural tanks prior to block erection. Use free standing tanks where feasible.
- Complete block painting in paint facility prior to erection

Interim Products

Configure blocks with at least one flat surface wherever feasible, to facilitate assembly and to provide enclosed spaces for functions not amenable to unitization, such as workshops and stores. Maximize the use of outfit units by incorporating the following.

- System units which can be standardized, vendor furnished
- Large integrated units, possibly integrated with ship structure at the assembly stage

Having defined the major interim products, the next priority is the assembly and erection sequence. An erection sequence and schedule is created, based on the baseline erection schedule. This schedule, represents the current capability of a shipyard. In the engine room area, adjustments are made to provide for:

- Provision of open ("blue sky") time for unit the erection schedule and assembly sequences loading;
- Opportunity for joining blocks into grand blocks;
- Acceleration of Zone 4 erection schedule to support shaft installation & alignment; and
- Late installation of the main engine.

Supporting the erection sequence, the following approach is recommended for the assembly of interim products in preparation for erection on berth.

a) Block assembly and installation of in-tank piping, structural attachments and foundations,
b) Grand block assembly of two or more blocks, outfitting of grating/pipe lane units, selected pipe assemblies and foundations, loading pallets for later installation,
c) Erection on-berth,
d) Loading of any remaining outfit material during the open period prior to erection of the next block. This includes major components and units which are costly, have a critically long lead time, or are too large or heavy to load on-block.

The engine room block/grand block erection sequence are shown in an erection schedule. For each block, the sequence and schedule allowed for one week of open time to permit on-berth installation of outfit units and pallets. In addition, the machinery casing area is kept open to allow two weeks for main engine installation starting ten weeks after keel, completing just prior to deck house erection.

The erection sequence and schedule is followed by development of interim product assembly sequences which define how these products are combined prior to erection on berth. The logic and criteria used included:

- Assembly of subunits and units within the unit shop, including the integration of vendor furnished units where appropriate;
- Assembly of grand units wherever feasible, breaking these units for loadout where necessary;
- Installation of grand units/units on grand blocks prior to erection on-berth. It is assumed that on-berth material pallets will also be loaded on the blocks prior to erection; and
- Units too large or heavy to load at this stage will be loaded on berth.

The results are recorded in a series of process flow charts, one for each grand block involved.

Finally, using the erection schedule and assembly sequence described above, material required dates, defined in terms of weeks before or after keel, are determined. Using material lead times, the required time for order placement for critical material is determined. It is found that a minimum interval of 12 months is required between contract award and keel to allow for the timely receipt of long lead material in support of the production strategy. With this minimum time established, the remaining 6 months in the target 18 month schedule are divided between the on-berth and overboard periods.

DESIGN REVIEW PROCESS

The design review process should be as open and objective as possible, giving the opportunity of discussions between the design team and the steering committee or its spokesperson.

The design team should present the design development, detailing the relevant points such as build strategy and metrics. Then the steering committee, together with the team, must spend the necessary time in analysis, discussion and clarification of design issues. This is best done on a one on one basis. This allows individual interface between steering committee and team members as each steering committee member reviews each system design storyboard.

In the end of the this analysis phase, the team and the committee should meet to discuss the results and to capture comments and action items.

A single list of comments requiring action should be developed and agreed upon. The team answers should be addressed as soon as possible in order to incorporate the comments into the design.

Figure 11 provides the recommended in-process design review process.

UNIT DEVELOPMENT

The following definitions are applied to unit levels.

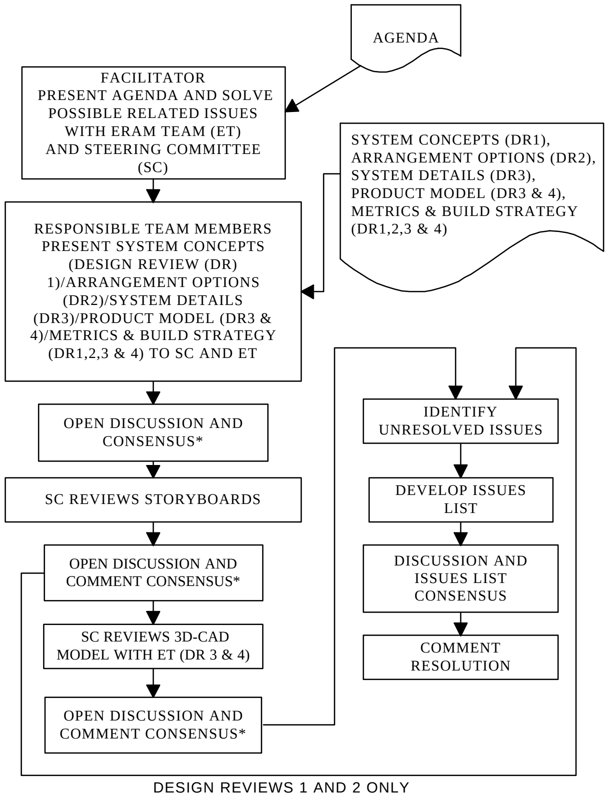

Figure 11 Design Review Process Flowchart

Level 1 - On-Block Outfit

The installation of individual components and systems on hull structural blocks. This approach minimizes miscellaneous steel but requires heavy-lift capability (600-800 tons) to avoid extensive on-board construction.

Level 2 - Functional Units

The integration of functional pipe and machinery skids normally dealing with major sub-elements of individual functional systems. This approach moves significant complex piping and machinery installation from on-board to on-unit but requires more secondary structure and design integration.

Level 3 - Large Integrated Units

The integration of large machinery units including all pipe, machinery and electrical components and systems in a geographical area of an the engine room. This approach effectively moves the majority of piping, machinery and electrical work from on-board to on-unit, but it requires a higher level of design integration and more secondary steel work than Level 2 as the units are larger and require additional support structure for lifting and handling..

Level 4 - Standard Machinery Units

Similar to the integrated machinery units described above, these units include pipe, machinery and electrical work in a given geographical zone of the ship. In addition, through the use of parametric design and a high level of planning prior to developing the machinery arrangement, some foreign yards have been able to standardize the structural framework and system interfaces such that all machinery units across a series of ship types and sizes utilize standard structural and system interfaces. This approach requires the highest level of pre-preplanning and design integration. Secondary steel work requirements are similar to Level 3.

The build strategy concepts and the level 2 units should be identified in the early stages of the design development. See Figure 12 The logical grouping of distributive system runs must also be considered in the

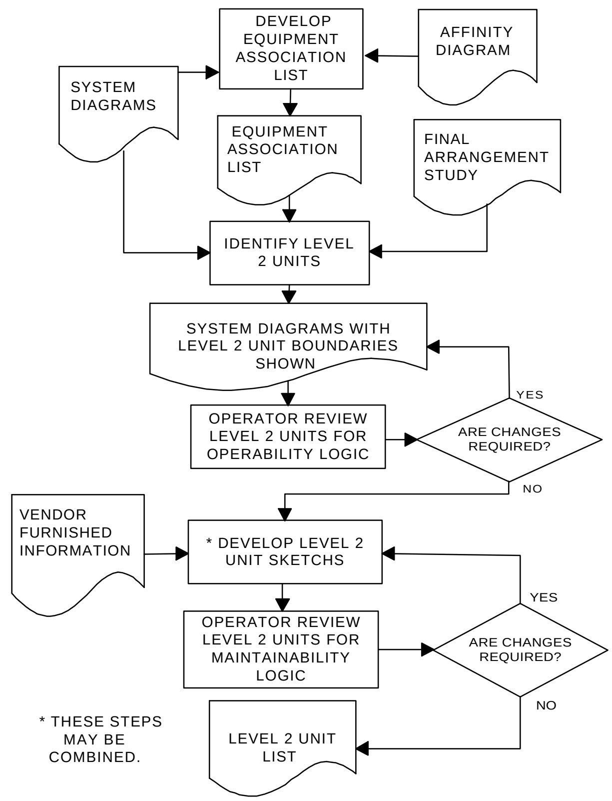

Figure 11. Level 2 Unit Development Flowchart

early stages.

Tools such as affinity diagrams, Figure 10, or equipment association tables should be used to guide unit definition. The engine room arrangement should be developed trying to place the potential level 2 units in suitable locations, taking into consideration the block breakdown and pipelane positions. Based on the tools used for system development, a list of level 2 units should be developed.

Parallel to the arrangement development, level 3 units should be identified (See Figure 13) and the component locations should be adjusted in order to accomplish this level of unitization.

Finally a complete list of units should be developed, presenting what components are included on level 2 units, level 3 units and block assemblies.

The following unitization concepts should be applied to the engine room design development:

- Maximize level of unitization, thereby avoiding work onboard;
- Maximize the use of pipelanes and cablelanes, to minimize work onboard; and

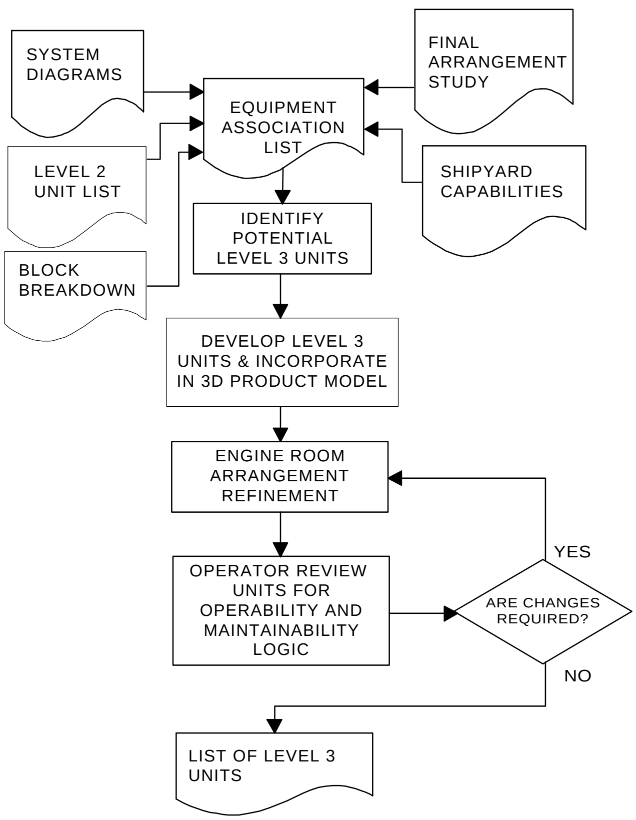

Figure 13 Level 3 Unit Development Flowchart

- Avoid the use of ship structure as a part of any unit.

METRICS DEVELOPMENT

The use of metrics is a key element of the Strategic Design Method and the development of metrics are an integral part of the development of the Strategic Design Brief. The process for metric development and its integration into the Strategic Design Brief is shown on Figure 14.

Strategic Design Brief

The Strategic Design Brief is a document which is created in an intensive 24 hour (3 working days) period to accomplish the following:

- Define the design problem with the agreement of all, including management;
- Shape a strategy framework to guide the design thinking;
- Generate creative design solutions;
- Develop a design measurement system; and
- Create a "next steps" action plan.

The basic concept of strategic design method is to identify, at the start of a project, the desirable

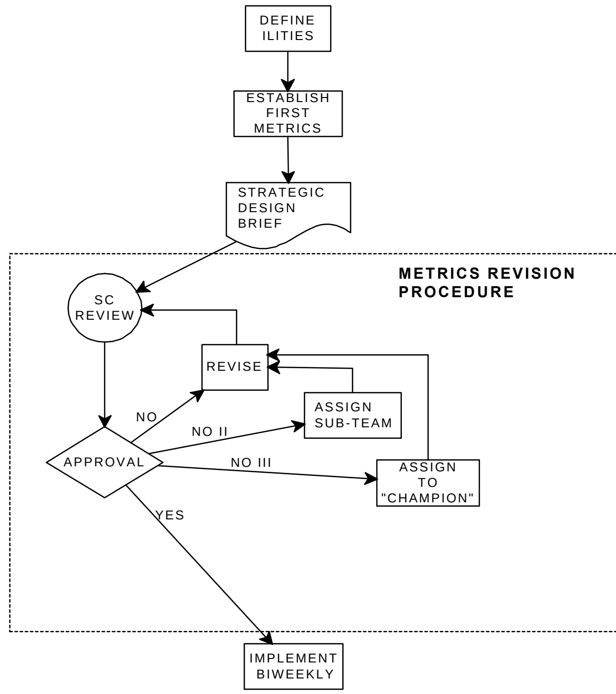

Figure 14. Metrics Development Process Flowchart

properties ("ilities") of the final product and design process, set goals for each property, innovate solutions strong points in both the design process and in the final product. They keep the design team and management in touch with the original concepts of the project, and indicate where more work is needed to achieve project goals. With buy-in, they are an agreed upon method between the team and management for measuring project success in-process. Post process, it is ultimately the customer that measures this success.

The design process is the most critical element to drive to consensus in the early stages of the project. All of the "ilities" of the process must be considered while innovating solutions. Attention must be paid to minimizing expenditures of effort ("ings") which achieve little progress towards the goals.

Metrics Concepts and Objectives Definitions

For the achievement of these goals, and set up a measuring system (the metrics) which will indicate whether the goals are being approached and where effort must be focused to achieve the project objectives.

Metrics are essential for indicating weak and the basic

method for establishing a metric is to look at the intent of the metric, brainstorm all of the major influences (the ilities) for that metric, and select 5 to 8 key drivers for that metric that are measurable. Then compare those 5 to 8 key drivers to the baseline to establish a reference. The normalized 'baseline ratio' has a goal, boundary and start value based on these values of the drivers compared to the baseline. Team progress is always tracked against these values. The concept of the boundary value is the minimum required to break into the market.

Brainstorming and selection of key drivers is conducted by the team. This session is lead by the most skilled or knowledgeable people of the team in each of the metrics. The open discussion within the team will ensure quicker team buy-in than forming a subteam to develop recommendations for team buy-in.

Buy-in of the metric is essential to the success of the team, if the Steering committee has rejected a metric recommendation for a second time, it may be necessary for a subteam to review metric basics. A quick review of these basics will indicate which metrics are in need of revision, this may include a redefinition of the 'ility'. The likelihood of metric buy-in is increased if the complexity and time required to calculate the metric values are reduced by remembering that team buy-in does not mean 100% satisfaction of all the stakeholders. Once Steering Committee buy-in has been achieved, subteams or individuals are assigned to develop the measurement tool for each metric. This tool is submitted to the team for buy-in and then the Steering Committee again following the process outlined in Figure 14.

CONCLUSION

The application of the IPPD processes to the ship design process at U.S. shipyards can significantly reduce the man-hours and duration to design commercial engine rooms. This concept can be effectively applied to the entire ship design process if shipyard management fully endorses and supports a corporate wide IPPD training program. In addition the concurrent incorporation of customer requirements can enhance customer satisfaction and lead to repeat orders.

The processes that each team should develop to enhance their success in an IPPD environment, listed in descending order of importance, follow.

Consensus Agreement Process

Consensus basically means the team is in agreement on an issue. This process should be the very first process invoked by a new team because it allows the team to make decisions. Having this agreement defined in writing is absolutely necessary to enable a team to function.

Team Norms Development Process

Team norms must be developed to insure that all team members follow certain standards that each team member has agreed upon. The standards will range from how work should be presented to mutual respect for each other. The amount of importance that the team places on how they treat each other as individuals can directly affect the output of a team. Norms are created to address member's concerns at the onset of team building so that all team members are assured of " riding the same bus down the same road to reach the same goal".

Meeting Management Process

A meeting management process is necessary in order to efficiently utilize the attendees time and capture and disseminate the results of the meeting. There are three basic types of meetings used to manage an IPPD team. The general meeting attended by all team members is used to discuss team issues. The Core Team meeting is used to discuss technical issues and major operating decisions. The Week In Review Meeting (WIRM) is used to manage the team and maintain focus of the overall objectives and goals of the project. This WIRM is the most important meeting tool used to manage the team.

Peer Review Process

The Peer Review is a tool that gives the team members a chance to confidentially evaluate their peers performance and make comments in a positive manner. When constructively done this is a excellent self improvement tool. This is an essential element to a successful team approach but one that must be owned by the team and properly conducted to be beneficial. The process could be modified to include sharing each individuals results with the team.

Team Member Performance Appraisal Process

The team member performance appraisal is a tool that is used to provide feedback on a team member's "TEAM" performance to his/her supervisor. Many team members will no longer have daily or even weekly contact with their actual supervisors due to their presence on a team. This process is created to fill that communication gap. It is very important that the team own/develop and update this tool.

Personal Conflict Resolution

Personal conflicts within the team is one of the most disruptive elements of the team process. They cause communication shutdown and team polarization resulting in loss productivity. It is essential that conflicts between team members remain within the team. Team members who take personal conflicts with other team members to persons outside the team should be subject to disciplinary measures that will be determined by the team as appropriate to the occasion.

Subteam Assignment Process

In order to improve team efficiency a process must be in place to prevent lengthy discussions. The subteam assignment process appoints a subteam (or expert) to develop a strawmam or make a decision to be presented to the team for buy-in.

Action Item List Process

The action item process identifies new tasks that are not addressed in the schedule. These new additional tasks are one of the primary reasons schedules are slipped. The action item list serves three purposes:
It tracks the status of the new items
It provides a simple method to prioritize new tasks and
It provides the basis for schedule changes or requests for additional support is such action becomes necessary.

Internal Approval Process

Throughout each of the design phases, team members who identify improvements to the current process or design must be given the chance to present their ideas to the team. A procedure for internal approval to allow all team members to have a chance to convey their thoughts and ideas to the rest of the team is an important tool. Using this tool not only increases awareness within the team but also promotes synergism and helps produce a better process and product.

Product Design Milestones Identification and Change Procedure

The milestones and principal dates are identified in order to develop the project schedule. The milestones to be identified are those related to the process design development as well as those related to the product design.
The milestones and principal dates initially identified may have to be revised due to issues not included in the initial schedule. A task to be included in the schedule is "schedule up-dating", which should be provided at regular intervals.

Owner/Operator Participation Procedures

In order to effectively integrate the voice of the customer through the design process it is recommended to have participation from an owner/operator in the form of a chief engineer. The process can effectively utilize this valuable resource and ensure that a dynamic partnership is created between shipyard and customer.

Process and Product Metrics

The use of metrics is a key element of the IPPD process. Metrics can be a powerful tool to improve both the product and a team's social behavior. The concept of process and product metrics is to set goals and use an in-process measuring system (metrics) which will indicate whether the goals are being approached and where effort must be focused to achieve the project objectives. Metrics are essential for indicating weak and strong points in both the design process and in the final product They keep the design team and management in touch with the original concepts of the project, and indicate where more work is needed to achieve project goals. With buy-in, they are an agreed upon method between the team and management for measuring project success in-process. Post process, it is ultimately the customer that measures this success.
The in-process measurement system should go beyond the traditional methods of measurement for the common three - Schedule, Performance and Direct Cost. Therefore the understanding of metrics and the effect of such on both process and product, along with the conclusions that are drawn are difficult to agree upon. Especially for those persons outside of the team. To this end it is important that metrics be used only to show direction and guide a team towards success.

Cad Subteam/System Engineer Interface Process

The CAD designers and the CORE Team must develop a process to facilitate the exchange of information between system engineers and the CAD subteam. This process should be developed to reduce confusion between team members, eliminate duplicated information being submitted to the CAD designers and to document the information being transferred between the system engineers and the CAD designers.

Vendor Information Management Procedure

This procedure provides a method by which Vendor Furnished Information (VFI) is requested, received, controlled and reviewed for conformity to specific project requirements. Each project may be set up in a different environment and requirements should be established to meet the shipowner needs. Some VFI can be available immediately from shipyard files or system engineers. Other VFI, shipowner specific vendor requirements, may be very difficult to obtain. This can be easily resolved through a close working relationship with the customer. Vendor Furnished Information must be provided concurrently with the engineering work during Phase 1.

Design Review Process

The design reviews shall be conducted in compliance with the IPPD approach of in-process review, evaluation, and approval. The design reviews shall be limited to the current phase of the project that is being addressed.
The goals of the design review process are as follows:

- Time Phase the Buy-In Process
- Promote Concurrent Incorporation of Comments
- Maximize the Development of the Project Final Report Elements

Ship s Systems Integration Process

In the design of the ship's systems there are many interface points that must be addressed. The identification of these points of interface and the proper integration of them is essential to the design process.

Information Storage/Back-Up/Retrieval Procedures

All enterprises require a plan for managing all technical and business data in order to design, build, and support a product through its life cycle. The implementation should be distributed in order to take full advantage of the networking and processing capabilities of the enterprise and to accommodate the possibility of participating within a virtual enterprise. Backups should be performed on a daily basis. The relational database used to support the product model should be unloaded nightly to text

files. All files which have been accessed in the previous days should be written to tape. At the end of the week and the month, and all files on the system should be written to tape. Monthly tapes should be archived.

Visit Process

Team visits to ships, vendors and related facilities to gather information, learn operational and maintenance characteristics of various equipment, and increase the shipboard knowledge of the team are essential. The visit process is created to increase the effectiveness and document the results of the visits.

Capture Lessons Learned

As part of the IPPD design process there is a need to capture any lessons learned in either resolving a problem, achieving a goal or finding a short cut to a solution. By recording the process, team members can refer back to it for answers or to avoid past problems.

User s Guide Editing Process

The 'User's Guide' is the **product** of the process. In order to improve the process, the process itself must be documented and a means to rapidly incorporate such improvements and disseminate them to all team members must be in place. This Guide should be a "living document" with "continuous improvement" of the document occurring as lessons are learned.

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Product-Oriented Design And Construction Cost Model

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ABSTRACT

Navy ship cost estimators traditionally estimate the cost of ships using system-based, weight-driven cost models. This approach has proven adequate in estimating the cost of ships with similar designs built using the same processes. However, this approach is not sensitive to changes in production processes, facilities, and advanced manufacturing techniques. In an effort to work more closely with industry to link ship design, manufacturing, schedule and costs, Naval Sea Systems Command sponsored the Product-Oriented Design and Construction (PODAC) Cost Model Project. This paper discusses the efforts and results of the PODAC project to date.

The aim of the cost model is to improve techniques for analyzing issues of ship cost reduction, advanced construction techniques, modular construction, new technology benefits, industry consortium and teaming arrangements. The model will enhance the Navy s and industry s ability to provide accurate, timely and meaningful cost feedback from cost analysts to ship designers and from production to design. By better relating to the actual construction process, such as interim products and stages of ship construction, the state of the art can be advanced by providing essential knowledge for effective decision making and program management. This should ensure cost effective choices and enhance the buying power of the Navy within its budget limitations. The PODAC cost model should be an invaluable tool to the shipbuilding industry as it works to improve its global competitiveness.

NOMENCLATURE

ATC Affordability Through Commonality
CER Cost Estimating Relationship
GBS Generic Build Strategy
G/PWBS Generic Product-Oriented Work Breakdown Structure
IPT Integrated Product Development Team
NSRP National Shipbuilding Research Program
PODAC Product-Oriented Design and Construction
PWBS Product Work Breakdown Structure
SWBS Ship Work Breakdown Structure
WBS Work Breakdown Structure
QFD Quality Functional Deployment

INTRODUCTION

The U.S. Navy has traditionally estimated the cost of ships using system-based, weight-driven cost models. This approach is not sensitive to changes in production processes and advanced manufacturing techniques. In an effort to link ship design, manufacturing processes, schedule and costs, Naval Sea Systems Command (NAVSEA) Mid-Term Sealift Ship Technology Development Program (MTSSTDP) and Affordability Through Commonality Program (ATC) sponsored the Product-Oriented Design and Construction (PODAC) Cost Model Project. The project is being closely coordinated by David Taylor Model Basin's Shipbuilding Technology Department with the MTSSTDP Generic Build Strategy task which includes the development of the Generic Product-Oriented Work Breakdown Structure (GPWBS) described in the concurrently published report, *Towards a Generic Product-Oriented Work Breakdown Structure.* See Reference [1].

A functioning prototype of the PODAC Cost Model was developed last year by a Navy/Industry Integrated Product Development Team (IPT). This team included the co-developers of the model, Designers and Planners Inc., the University of Michigan Transportation Research Institute (UMTRI), and SPAR Inc., as well as participants from the Navy's cost and design community, and two shipyards, NASSCO and Avondale. The team demonstrated the PODAC Cost Model prototype to a Steering Committee which includes members from NAVSEA's Program Management, Design, and Cost organizations, as well as members from the five major U.S. shipyards, Avondale, Bath Iron Works, Ingalls, NASSCO, and Newport News. Upon viewing the demonstration, all five shipyards expressed interest in working with the Navy to further test and enhance the model in the near future.

BACKGROUND

The Product-Oriented Design and Construction (PODAC) Cost Model Project is an effort to develop a cost model which is

sensitive to the way that shipyards build ships today, as well as being sensitive to how they may be built in the future. The model must accommodate ever-improving production processes and major innovations in ship designs, equipment, and facilities. The vision and goals for the development of the PODAC cost model were set during a workshop in 1994 to determine the desired attributes of a new Navy cost model.

The goal of the PODAC Cost Model is to utilize a product-oriented work breakdown structure and group technology, as well as to accommodate alternative work breakdown structures. The new model will be a tool for smart business decisions in the areas of

- technology assessments,
- engineering trade-offs,
- design and construction processes, and
- ownership cost assessments.

Strengths and Weaknesses of Current Navy Cost Model

The development of the PODAC Cost Estimating Model was initiated by the Navy in order to tie together ship design, production processes and costs. Currently, the Navy estimates ship costs using traditional weight based cost estimating relationships and the Ship Work Breakdown Structure (SWBS) which is a functional breakdown of the ship by systems. Traditional weight based estimating relationships are broken out by labor, material and overhead. These are usually in the form of dollars per ton for material costs and man-hours per ton for direct labor. A percentage for overhead costs is applied to direct labor costs. These weight based cost estimating relationships do not reflect improvements that may occur in the production process. For example, if a new welding technique is used which takes 25% less man- hours per foot of weld, no change would be reflected in cost, because there is no change in the weight of the ship. Therefore, if a change in design or production process has no impact on weight, then the cost estimate will not change.

The SWBS structure is based on systems that are distributed throughout the ship. There are no geographical or zonal boundaries using SWBS. SWBS is linked to design features and functional characteristics of the ship, providing adequate information for estimating in the early design stage. However, a ship is actually constructed by zones, or geographically discrete products. Therefore, SWBS has no relation to the way a ship is built. These deficiencies in the cost estimating relationships and breakdown of the current system were aptly noted by Walt Christensen at the NSRP symposium in 1992,

> *Ship construction cost estimating relationships are derived from historical data reflecting past accounting methods and performance. Cost reductions resulting from newly adopted and developing shipbuilding technologies and production methods are not reflected in the existing historical based cost estimating techniques. Advanced shipbuilding technologies typically involve a modular, product oriented approach which cuts across elements of the existing SWBS. Thus, even the basic structure of the current approach to ship cost estimating is of questionable relevance for modeling the ship construction processes and cost estimates of the future.* See Reference [2].

There was very little dispute over the need for a better cost model. Rather than developing a model from scratch, however, the Navy wanted to identify the strengths and weakness of their current cost model and build from there. The strengths and weaknesses of the Navy's current model were discussed at the July 1994 PODAC Cost Model Workshop and are summarized below.

Strengths

- It is based on decades of historical data;
- It is defensible and reproducible;
- It is relatively simple (not overly burdensome with detail);
- It is tonnage based, requiring minimum design information to develop an estimate;
- It has been an accurate predictor of ship cost in the past; and
- It is adequate for budgeting and financial reporting.

Weaknesses

- It does not break down costs the way that ships are built;
- It is not useful in making design decisions;
- It does not relate to the design characteristics of a ship
- It can not address the impact of new technologies or processes; and
- It provides no feedback for engineering or production.

The general agreement of those attending the workshop was that the Navy's current shipbuilding cost model is of little use in providing information to make decisions regarding cost reduction in the design or production of ships. Therefore, the Navy needed to adopt new cost models which define the major design, production, and operational cost drivers as well as provide information necessary to make management decisions to reduce costs.

Steering Committee

In order to understand the concerns of the various Navy customers of this model, a Steering Committee chaired by the Cost Estimating and Analysis Division, NAVSEA 017, was formed in October 1994. This committee includes the SEA 03 sponsors as well as members from the Surface Ship Design and Engineering Group, NAVSEA 03D, the Ship Research, Development and Standards Group, NAVSEA 03R, NAVSEA 017, representatives from the SC21, Sealift, and LPD 17 Program Offices, the Cost and Economic Analysis Branch, NSWCCD 21, and the Shipbuilding Technology Office, NSWCCD 25.

The purpose of the Steering Committee is to provide to the IPT:

- Strategic leadership and oversight;
- Resources/Facilitization; and
- High level goals and objectives

The Navy Steering Committee also felt that for the model to be used successfully, it should have value to and be accepted by the shipbuilding industry. In that light, the Steering Committee just recently expanded its membership to include management from the five major U.S. shipyards.

Concept Exploration and Evaluation

The first year of the project involved concept exploration and evaluation. A search was performed to identify existing cost models which would meet the Navy's need for a new cost model. Three existing models were identified as being pertinent to the task at hand and three additional concepts were explored. The six producers of the models were:

1. System Programming, Analysis & Research (SPAR), Inc.
2. Jonathan Corporation,
3. Decision Dynamics, Inc.,
4. University of Michigan Transportation Research Institute (UMTRI),
5. John Dougherty as a subcontractor to Designers and Planners, Inc., and
6. DAI as a subcontractor to Designers and Planners, Inc.

A Navy Evaluation Team was set up to evaluate the models and make recommendations for continuing the effort of developing the PODAC Cost Model. The Navy Evaluation Team consisted of a chairman, facilitator, and nine representatives from the Navy cost, design, and program management communities. The criteria used for the Navy evaluation were developed by the NAVSEA PODAC Cost Model Steering Committee. This ensured that the results of the evaluation addressed the needs of the sponsors. The committee grouped the criteria in order of importance by assigning a high, medium, or low value to each. Listed below are the twenty-nine criteria and their stated importance.

<u>High Rank</u>

1. The model should be capable of performing relative cost estimates for comparative purposes and trade-off studies.
2. The model should be sensitive to Schedule.
3. The model should be able to measure the cost impacts of Alternative Configurations (ship/system/product).
4. The model should be capable of performing cost estimates at all stages of Design Maturity (Feasibility, Preliminary, and Contract).
5. The model should be sensitive to Work Environment (Stage).
6. The model should be sensitive to PWBS.
7. The model should be able to measure the cost impacts of Alternative Arrangements.
8. The model should be able to measure the cost impacts of design choices of materials/equipment.
9. The model should take into account rate effects, learning curves, and other quantity/volume related functions.
10. The model should be capable of converting from PWBS to SWBS and back.
11. The model should be able to measure the cost impacts of Alternative Manufacturing Processes.
12. The model should take into account acquisition strategy.
13. The model should be capable of performing budget quality cost estimates.

<u>Medium Rank</u>

14. The model should be integrated with CAD2.
15. The model should be sensitive to Sequence.
16. The model should be capable of performing rough-order-of magnitude cost estimates.
17. The model should be easy to use.
18. The model should estimate total Life Cycle Cost.
19. The model should be able to measure the cost impacts of varying standards and specifications.

<u>Low Rank</u>

20. The model should be able to measure the cost impacts of design choices affecting spatial density.
21. The model should be sensitive to overall industrial base.
22. The model should be sensitive to Facilities/Limitations and Constraints.
23. The schedule to complete development of the model is an important factor.
24. The model should be sensitive to the business base for specific yards.
25. The model should be evaluated on the development costs or cost to purchase a license agreement.
26. The model should be evaluated on the feasibility of acquiring sufficient cost and technical data to populate it and the cost to acquire the data.
27. The model should be sensitive to Laws and Regulations.
28. The model should be sensitive to Make/Buy choices.
29. The model should be capable of performing investment analysis.

PODAC Cost Model Concept Selection

The Navy's evaluation team found, after reviewing and ranking the six models and concepts, that none of the models met all the Navy's requirements. Thus developing a hybrid of the concepts was the best approach. The recommendations of the evaluation team were to:

Develop the PODAC Cost Model as a hybrid using features from the various concepts, which would include:

- an existing commercial model to minimize development time and provide a commercial user base to help support future improvements and maintenance of the model;
- the capability for early stage parametric costing with a top-down approach;
- an underlying cost database that supports a top-down approach;
- re-use modules for costing interim products; and
- a module to identify risk.

Establish an IPT to develop the PODAC Cost Model Specifications and the model itself. In addition to the chosen model developers, the team at a minimum should include a Navy design engineer, a Navy cost estimator, and representatives from each shipyard. This team should also develop the PODAC Cost Model System Specifications.

The conclusion of the evaluation team was that SPAR's model *ESTI-MATE*™ should be the starting point for the model, with John Dougherty of Designers & Planners, Inc. leading the development team and incorporating the concepts of the G/PWBS into the model.

PODAC Cost Model Development Plan Overview

Following the recommendations of the Navy evaluation team, an IPT was established to direct the effort of planning and developing a cost model which would have the capabilities discussed above. The team was selected to represent all of the

diverse perspectives necessary for producing an effective and useful cost model for potential customers of the model, i.e., both Government and Industry personnel.

The IPT used Quality Functional Deployment to translate the Steering Committee's criteria into functional characteristics of a cost model. The team determined the model must have the following functions to address the Steering Committee criteria and meet the needs of the shipyards:

- Cost estimates must be organized in both system-based and production-based accounting schemes so that both early-stage system-based designs and later-stage production-based designs can be accommodated,
- Cost estimates for early-stage system based designs will be produced by drawing from an historical database containing Cost Estimating Relationships (CERs) which are empirically related to system-level parameters like steel weight or propulsion prime mover/power output,
- Cost estimates for later-stage production-based designs will be produced by drawing from an historical database containing CERs which are directly related to production-level parameters like weld length or pipe length,
- cost estimates will be accompanied by prediction uncertainty probability distributions based on comparison of historical estimates with actual costs expended,
- cost estimates will be capable of reflecting data transmitted directly to the cost model by ship designers using design synthesis models and computer-aided design tools.

In order to accomplish the above functions, the development of the model was then broken up into the following functional modules (see Figure 1):

- SPAR/ESTI-MATE Core Cost Model: baseline cost-estimating module to which enhancement modules were added,
- Design Tool Interface Module: provides a link between PODAC Cost Model and various computer-aided ship design tools,
- Return Cost Module: provides mechanism for electronically entering and storing return cost data,
- WBS Translation/Mapping Module: used to translate shipyard-unique cost data and historical Navy SWBS cost data into the Generic Product Work Breakdown Structure and back,
- Parametric Module: enables designers and estimators to develop reliable cost estimating relationships for ship design parameters available at the Concept, Preliminary, and Contract Design Stages.

THE PODAC COST MODEL

The PODAC Cost Model is designed to enable shipyards and the Navy for the first time to estimate cost by

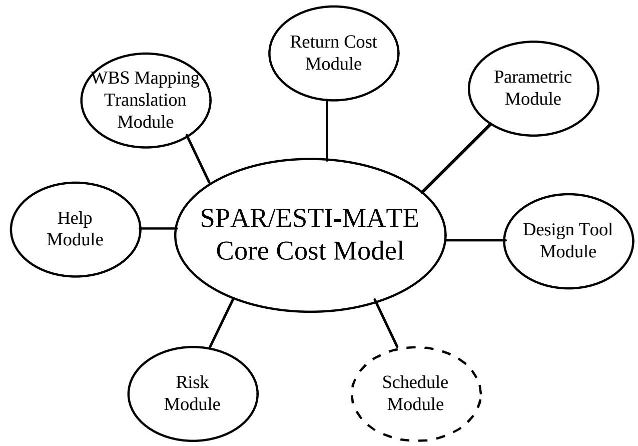


Figure 1. PODAC cost model development tasks.

analyzing the production-based return cost data collected in previous construction efforts. This data reflects the way ships are built using modern shipbuilding techniques and allows efficient analyses of man-hour expenditure rates that can lead to productivity improvements. These improvements can be achieved by upgrading facilities or changing inefficient processes.

Currently, new estimates are generated using a SWBS or SWBS-like system based accounting scheme because of the limited amount of design detail which is available to the estimators before a contract is actually awarded. However, once a contract has been signed, detailed design is performed and the production planners break up the construction of the ship using a production based work breakdown system to show what interim products will be produced where, when, and by what trades.

After work is performed, return costs are collected in the form of the yard's production-based system, not the system based structure for which the ship's cost estimate was developed. This creates an accounting disconnect between estimated and actual cost which has thus far prevented estimators from using production-based actual cost data to generate new ship estimates. The PODAC Cost Estimating Model knocks down the wall that isolates the estimating accounting scheme from the actual cost accounting, thus allowing the use of return cost data to generate new ship estimates. With the PODAC Cost Estimating Model new ship cost predictions can be made which reflect actual production-based data, thus improving the quality of the estimates and providing better information for reducing production costs earlier in the design stage.

The first two modules to be discussed, the Design Tool Interface Module and Return Cost Module are necessary for efficiently inputting the technical and return cost data needed in developing both detailed and empirical CERs for future ship or interim product estimates and design trade-off studies.

Design Tool Interface Module

The purpose of the Design Tool Interface Module is to provide a link between the PODAC Cost Estimating Model and various computer-aided ship design tools or product models. It is expected that these Product Models will soon hold all the cost and technical attributes associated with construction of a ship and its interim products.

The PODAC Cost Model is capable of importing technical data from design synthesis models such as the Navy's ASSET program, and from computer-aided design software like AutoCAD or Intergraph. In the future, this interface capability will allow ship designers to link directly with the PODAC CEM so they can quickly assess the cost impact of any design feature they may wish to consider.

Current capabilities that were demonstrated by the IPT were the importing of SWBS 3-digit weight estimates from the ASSET design synthesis model, as well as importing a Bill of Material directly from an AutoCAD drawing. The SWBS data can feed directly to the Parametric Module for formulating high level CERs. On the other hand, the Bill of Materials can be used for much more detailed estimating or trade-off studies. If a designer wanted to consider alternatives to a baseline configuration, the baseline drawing could be copied over, design changes made, the Bill of Material revised, and then the cost model would produce cost estimates for each of the alternatives, and feed the estimates back to the designer.

Return Cost Module

The purpose of the Return Cost Module is to provide a mechanism for electronically entering and storing return cost data in the form provided by individual shipyards as well as the capability to browse this data as entered or in the form of a Generic Product Work Breakdown Structure (G/PWBS).

The actual cost data collected at most shipyards is organized in a production-based accounting system, as shown in Tables I and II.

Table I shows a typical shipyard Work Order Record, the device used to plan the labor portion of a ship construction effort, and which establishes the data collection scheme for compiling actual labor costs.

Table II shows a typical shipyard Purchase Order, the device used to plan the material portion of a ship construction effort, and which establishes the data collection scheme for compiling actual material costs.

These two documents, the Work Order Record and the Purchase Order, collectively describe all the cost data collected for an actual cost report, so the PODAC CEM would ideally be able to accept all data elements in these two documents.

Collecting the data in the Work Orders and Purchase Orders for use in the PODAC Cost Estimating Model is straightforward. The Return Cost Module can be hooked to a shipyard's network to directly import Work Order Records and Purchase Orders. It would not be unusual for the number of Work Order Records and Purchase Orders for one ship to total more than twenty thousand. The time to input this data by hand would take hours. The PODAC Cost Model can be hooked up to a shipyard's network and import this data in a few minutes.

Because such data sometimes contains errors, there is additional work required to find and correct these errors in return cost files for existing ships. Working with thousands of data points at the Work Order and Purchase Order level is sometimes impractical. In order for this data to be more manageable and meaningful, the PODAC Cost Model uses the Translation/Mapping Module to aggregate the return cost at a more meaningful level.

WBS Mapping/Translation Module

The purpose of the WBS Mapping/Translation Module is to translate shipyard unique cost return and estimating data and historical Navy SWBS bid estimates and return cost data into one logical homogenous cost estimating database structure, the Generic Product Oriented Work Breakdown Structure as shown in Figure 2 [Reference 1], normalizing the data into a relevant format for further analysis. In addition to creating a homogenous database, the WBS Mapping/Translation Module also is used to overcome the obstacle of the organizational structure difference between estimated and actual costs.

The G/PWBS can help shipyards better identify their own cost drivers, and can provide them with a better basis to implement changes to their existing cost management systems if they see a benefit to do so. The G/PWBS is a well-organized, already-developed format that can work with their existing systems. The G/PWBS provides a way for a shipyard to better understand their own product-by-stage costs, especially if their existing cost management systems are not capable of providing good visibility.

<u>Shipyard PWBS-to-Generic PWBS Data Translation</u>

Because all shipyards use similar, but not identical, PWBS systems, it was necessary to develop a Generic PWBS capable of accommodating any shipyard's PWBS. The Translation/Mapping Module can map any yard's work breakdown structure to the three axes of the G/PWBS.

The first set of mappings is for the Product Structure axis. The PODAC Cost Estimating Model aggregates lower level return costs to zones (Figure 3), sub-zones (Figure 4), and blocks (Figure 5). The information to do this mapping is included on most shipyards' Work Order Records.

The translation of shipyard PWBS to G/PWBS provides the capability to import a ship set of work orders and populate the upper levels of the product structure as shown in Figure 6.

Work Order Records also provide the information necessary to map the shipyard's work type (Figure 7), stage of construction (Figure 8), and work center (Figure 9).

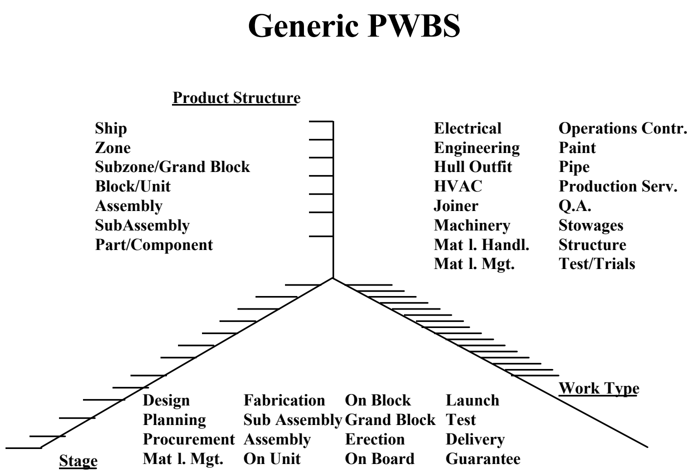


Figure 2. Generic Product-Oriented Work Breakdown Structure.

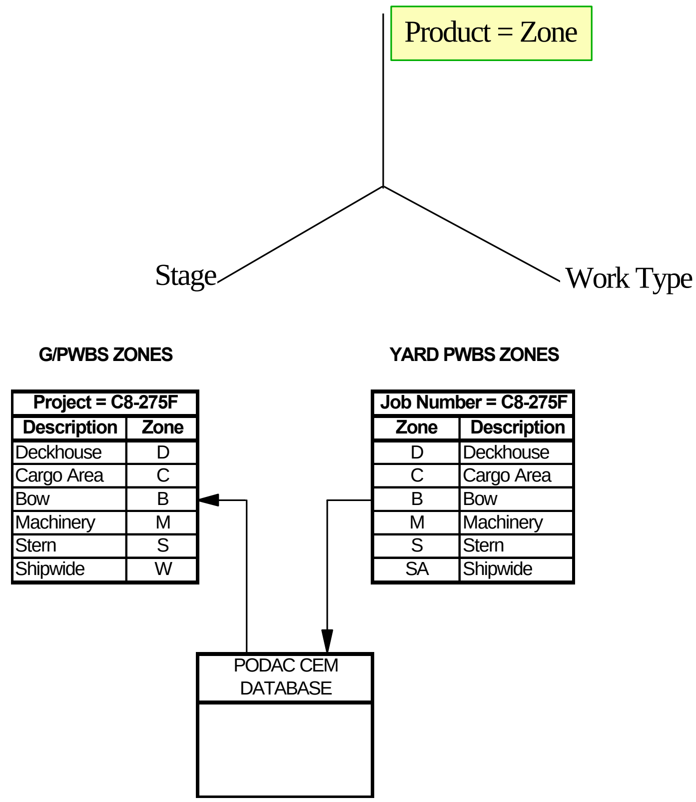


Figure 3. Mapping shipyard PWBS to G/PWBS, zone.

Ship	Cost Group	Wk Ord #	UoM	Qty	Zone	Unit	Est MH	Act MH	Pre MH	Tot MH	Work Cen	Plan Start	Act Start	Plan Comp	Act Comp
C150	xx F0 01	D6327	S	655	SW	0	24	25	0	25	907	7/8/91	7/12/91	9/31/91	10/2/91
C150	xx F0 02	D6144	S	950	SW	0	18	20	0	20	907	8/12/91	8/15/91	8/12/91	8/15/91
C150	xx F0 03	D6294	S	840	SW	0	20	17	0	17	907	7/18/91	7/12/91	7/18/91	7/12/91

Cost Groups	Description
xx 00 00	Engineering
xx F0 01	Manual burn/shear plates
xx F1 02	Machine burn/shear plates
xx F1 03	Roll and heat plates
xx F0 07	Blacksmith shop forming
xx F0 08	Pipe shop forming

Unit of Measure
T = ton
P = pound
L = linear foot
S = square foot
K = compartment

Zone
SW = shipwide
C = cargo
B = bow
M = machinery
S = stern

Unit
0 = not used
101 = ...
210 = ...
320 = ...

Man-hours
Estimated
Actual
Premium
Total

Work Centers
1 = Platen 1
2 = Platen 2
68 = Sheet Metal Shop
75 = Machine Shop
83 = Electrical Shop
907 = Plate Shop

Table I. Typical shipyard work order records.

Ship	Cost Group	Purch Ord #	UoM	Qty	Est $	Act $	Plan Arriv	Act Arriv
C150	xx F0 01	G4545	ea	20	7,000	9,500	7/8/91	7/12/91
C150	xx F0 02	H6898	T	950	12,500	10,800	8/12/91	8/15/91
C150	xx F0 03	M3095	S	840	25,700	24,600	7/18/91	7/12/91

Cost Groups	Description
xx 00 00	Engineering
xx F0 01	Manual burn/shear plates
xx F1 02	Machine burn/shear plates
xx F1 03	Roll and heat plates
xx F0 07	Blacksmith shop forming
xx F0 08	Pipe shop forming

Unit of Measure
T = ton
P = pound
L = linear foot
S = square foot
ea = each

Table II. Typical shipyard purchase order records.

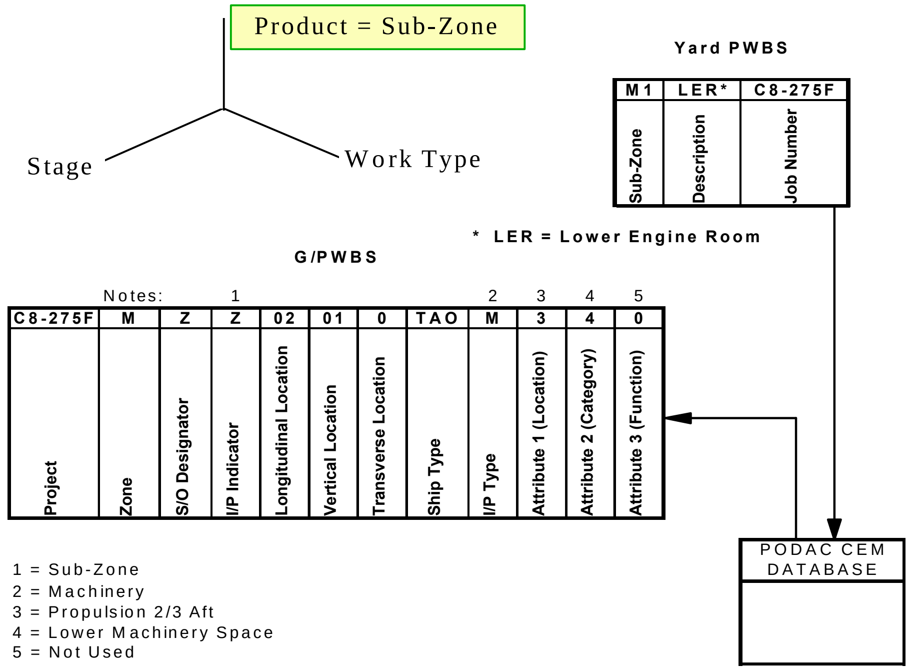


Figure 4. Mapping shipyard PWBS to G/PWBS, sub-zone.

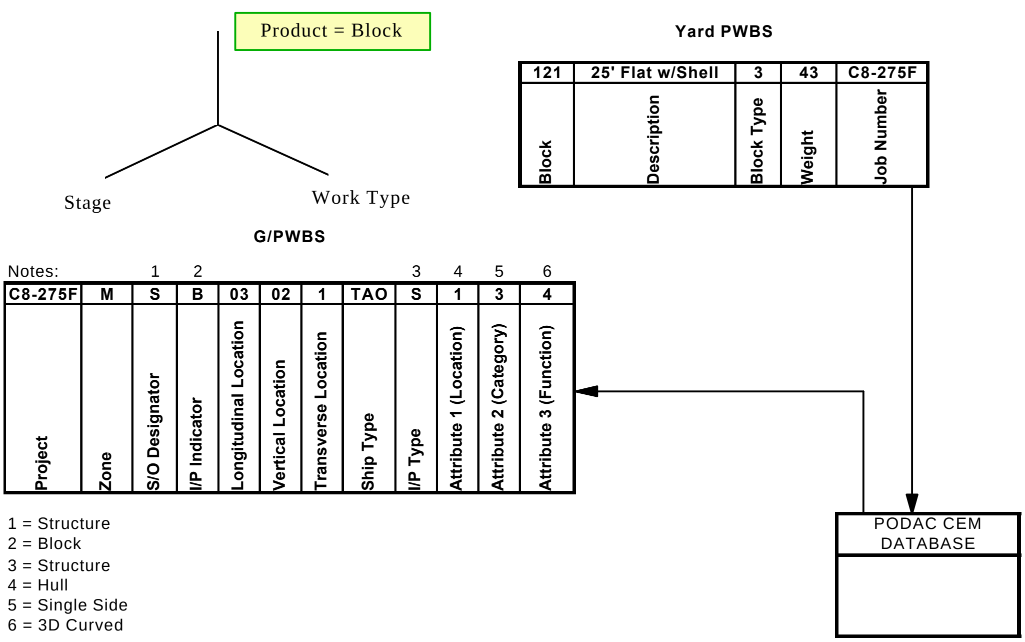


Figure 5. Mapping shipyard PWBS to G/PWBS, block.

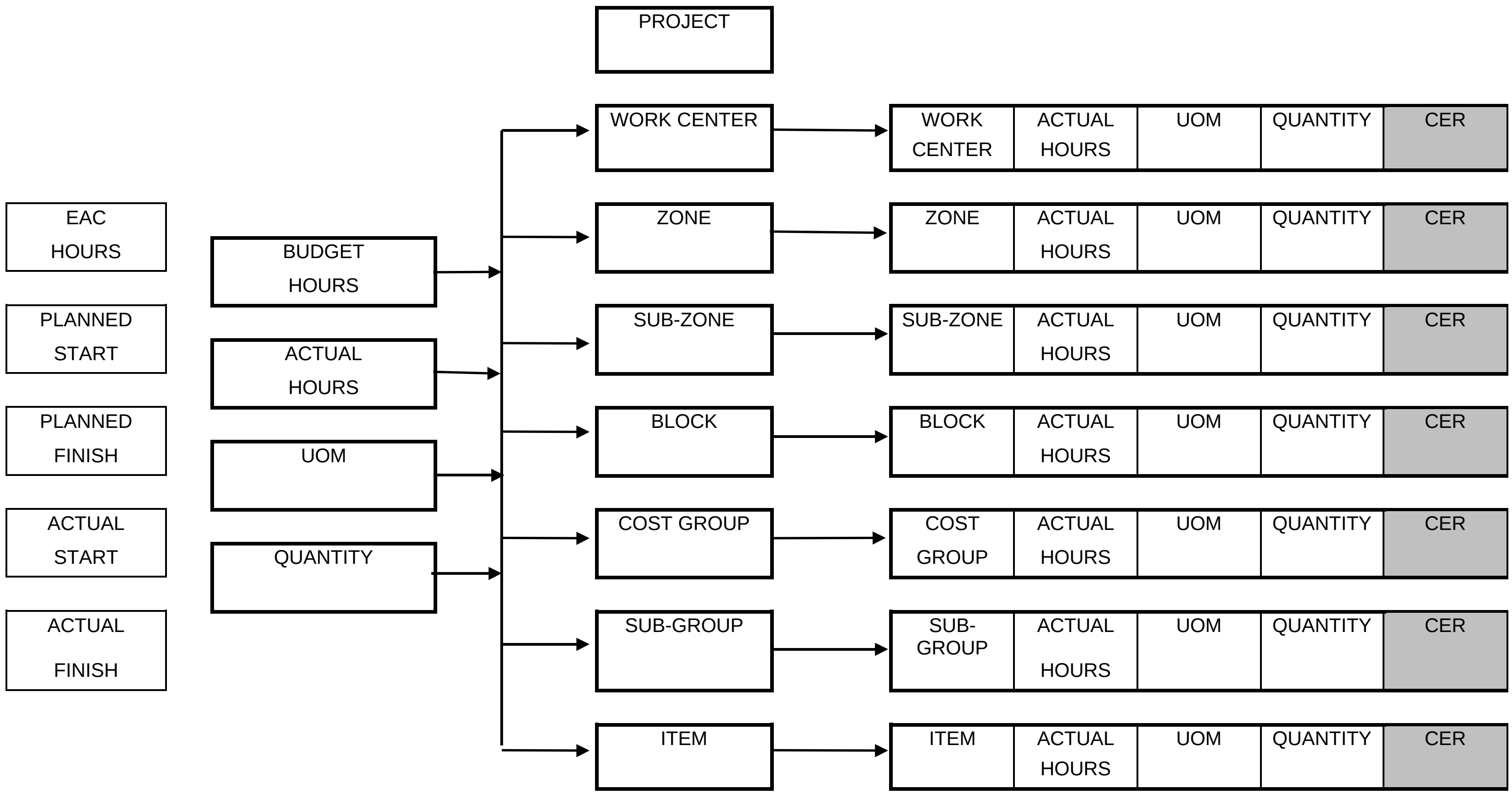
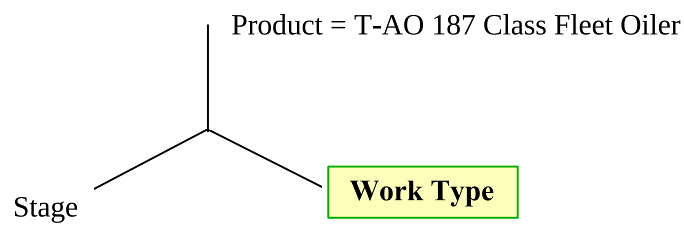
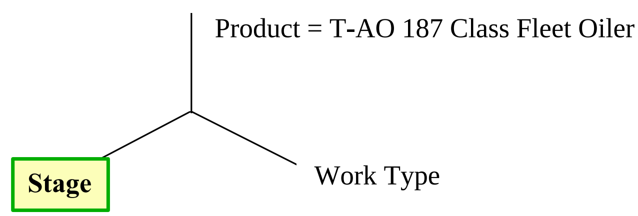


Figure 6. Populating upper levels of cost structure with an imported shipset of work orders.



G/PWBS Work Type	Shipyard Cost Code	Description
EG	xx	Engineering
HU	xx	Hull
SU	xx	Superstructure
JC	xx	Joiner
PI	xx	Piping
MC	xx	Machinery
EL	xx	Electrical
SM	xx	Sheetmetal
CY	xx	Carpentry
...	...	...
PD	xx	PDA & Delivery

Figure 7. Mapping work types.



G/PWBS Stage	Shipyard Stage	Description
FB	01	Fabrication
OU	02	Assembly (On-Block)
OO	03	On-Board
TT	07	Air & Hydro Tank/Compartment Test
AS/ER *	77	Rework
PU	98	Fixed Price Subcontractors
FB	F0	Pre-fabrication - Fit
SA	F1	Fabrication - Fit
AS	F2	Fabrication - Weld
ER	F3	Assembly - Fit / (On Unit)
AS/ER	F4	Assembly - Weld / (On Unit)
SA	W1	Erection - Fit / (On Board)
AS	W2	Erection - Weld / (On Board)
ER	W3	Miscellaneous - Fit
AS/ER	W4	Miscellaneous - Weld

* Pro-rated between Assembly and Erection

Figure 8. Mapping stages.

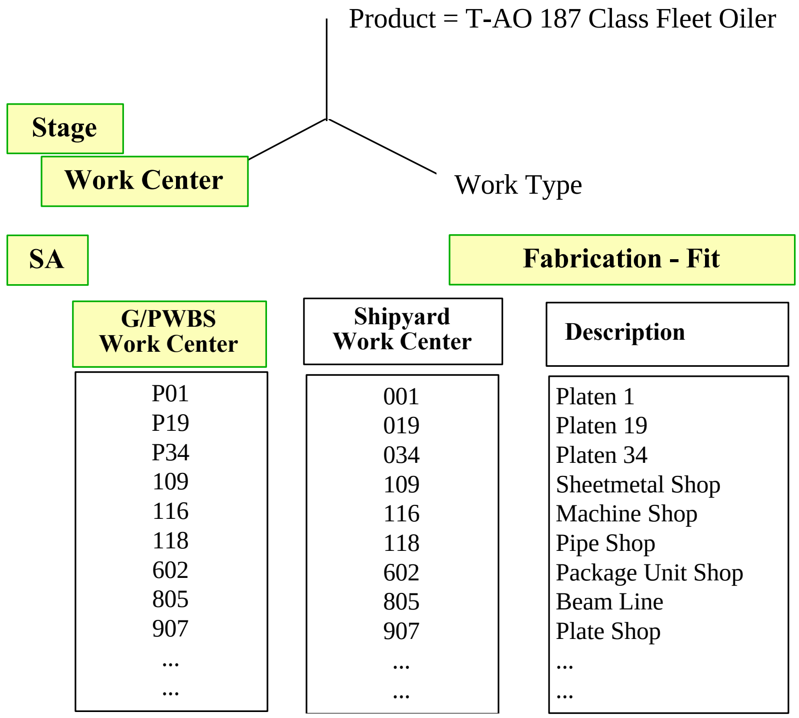


Figure 9. Mapping work centers.

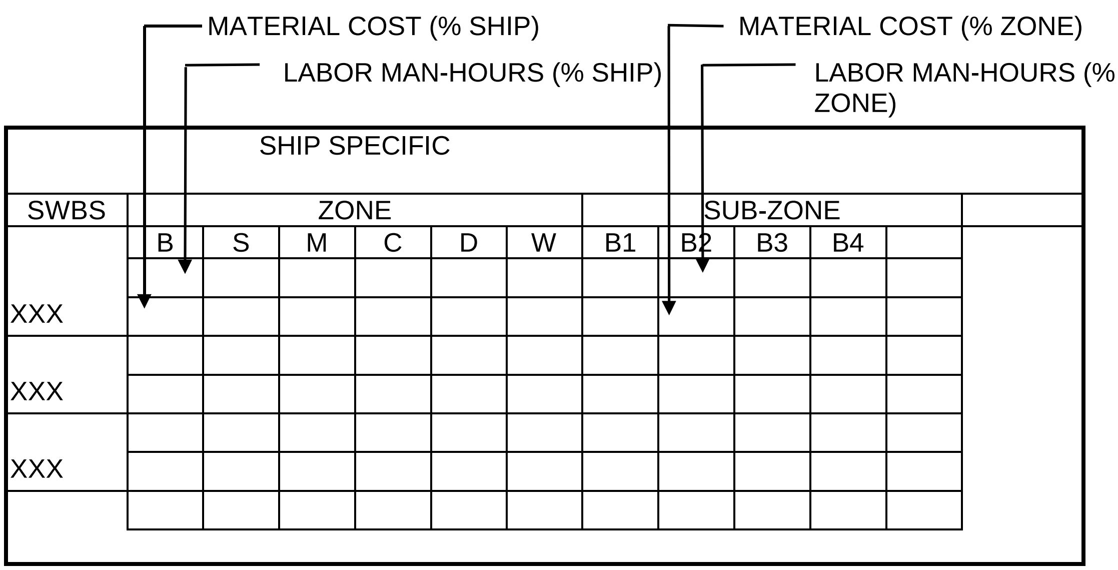


Figure 10. PWBS to SWBS translation template.

G/PWBS to SWBS Data Translation

The translation from the Shipyard PWBS to the Generic PWBS is straightforward and each element of one scheme maps

directly to one element of the other. However, for translating from the Generic PWBS to a system-based accounting scheme like SWBS, a unique set of templates must be developed for each ship type under consideration. Extensive judgment is required to allocate numerous portions of a PWBS data set to a single SWBS account. Developing a set of templates could be termed a major operation. It involves a careful analysis of the drawings and weight report which define a particular ship design, and allocating portions of the ship's cost elements, as organized by PWBS, to their SWBS counterparts. Without the ability to translate data from one organizational scheme to the other, the utility of the PODAC Cost Estimating Model would be greatly reduced.

Figure 10 shows a typical translation template. These templates would be used to translate from PWBS to SWBS, but once they are defined, they can be used inversely for translating SWBS data to PWBS as well.

Parametric Module

The Parametric Module enables designers and estimators to develop reliable cost estimating relationships for ship design parameters available at the Concept, Preliminary, and Contract Design Stages. The Parametric Module provides the mechanism for entering the parameters available at the various design levels for specified ship types, and their associated costs.

The PODAC Cost Model uses two types of CERs:

- Empirical CERs, which relate cost to system-level parameters like structural weight and propulsion prime mover/power output, or cost relationships for higher level interim products such as blocks or zones.
- Direct CERs, which relate cost to production-based parameters like weld length and pipe length.

Empirical CERs

The purpose of Empirical CERs (ECERs) is to provide a parametric approach for estimating construction costs at the various stages of design. ECERs will permit new ship cost predictions long before detailed information becomes available for directly translating actual production parameters into cost. The Parametric Module is structured to use a statistical analysis that carefully considers factors like ship type, complexity, and basic ship characteristics such as displacement, speed, individual system weights, hullform, and associated ship costs, so new ship cost predictions can be correlated empirically to those parameters. The concept of the Parametric Module is to develop forms of equations by which the user could either tailor the equations or automatically update their coefficients with actual return costs that have been imported into the database.

The IPT received assistance from the statistical department at UMTRI to develop the SWBS-based Empirical CERs. These ECERs were developed using a limited database of both Navy and commercial vessels which included ships of all types from 36-ft workboats to 265,000 DWT tankers. It was found that for the same ship type, many of the proposed parameters are dependent on each other. For example, steel weight is dependent on length, beam, depth, draft, and speed. The dependencies of various ship characteristics or parameters were determined by limiting the required number of variables within the equations Next, the data points were plotted to find the best form of the equations. For each stage of construction (concept, preliminary, and contract) linear and non-linear regressions were performed to derive ECERs for a variety of parameter combinations and forms of equations. The equations with least error were selected as the recommended ECERs.

At the concept level, the price of the total ship is a function of displacement (DISPL), speed, and a complexity factor (CF): $PRICE = CF \times A \times DISPL^{b} \times SPEED^{c}$.

Values for the coefficient A and exponents b and c would be determined by applying this equation form in a regression analysis of a user's database of return costs.

Because the cost data available to the IPT was for various ship types, it was necessary to use a Complexity Factor to normalize the data and achieve better equations. The use of Complexity Factors is not unique to the PODAC Cost Model. Complexity Factors are used in other models such as the NASA Cost Estimating Model and Lockheed Martin's hardware cost model, PRICE H. The Complexity Factor the IPT used is derived from a Size Factor and Ship Type Factor; Size Factor is $32.47 \times DISPL^{-0.3792}$. The OECD coefficients for Compensated Gross Tons were used for both the ship type and the ship size factors. Table III lists ship type factors for ships ranging from crude oil tankers to Navy Combatants. There was no OECD data for Navy ships, so the available costs of these ships were fitted to a curve with the rest of the ships, and new factors were derived.

SHIP TYPE	TYPE FACTOR
Crude Oil Tanker	0.80
Product Tanker	1.13
Chemical Tanker	1.25
Double Hull Tanker	0.90
Bulk Carrier	0.86
Oil/Bulk/Ore Carrier	0.95
Containership	0.96
Roll-On/Roll-Off	0.83
Car Carrier	0.61
Ferry	1.25
Passenger Ship	3.00
Fishing Boat	2.20
Tug	0.80
Combatant - Cruiser (Nuclear)	9.00
Combatant - Destroyer	8.00
Combatant - Frigate	7.00
Amphibious - LHA/LHD	7.00
Amphibious - LSD/LPD	5.00
Auxiliary - Oiler	2.25
Auxiliary - Tender	4.50
Naval Research	1.25
Naval Tug, Oceangoing	1.00
Coast Guard Icebreaker	4.50
Coast Guard Buoytender	2.00

Table III. Ship type factors for the PODAC Cost Model Parametric Module.

SWBS	LABOR MAN-HOURS	MATERIAL DOLLARS
100	$CF \times 177 \times Weight_{100}^{0.862}$	$800 \times Weight_{100}$
200	$CF \times 365 \times Weight_{200}^{0.704}$	$15{,}000 + 20{,}000 \times Weight_{200}$
300	$682 \times Weight_{300}^{01.025}$	$25{,}000 \times Weight_{300}$
400	$1{,}605 \times Weight_{400}^{0.795}$	$40{,}000 \times Weight_{400}$
500	$CF \times 34.8 \times Weight_{500}^{1.24}$	$10{,}000 + 10{,}000 \times Weight_{500}$
600	$310 \times Weight_{600}^{0.949}$	$5{,}000 + 10{,}000 \times Weight_{600}$

Table IV. Typical preliminary design stage equations for the Parametric Module.

SHIP TYPE	PD-337
DISPLACEMENT	45,900 TONS
SPEED	20.2 KTS
SHIP TYPE FACTOR	0.83
COMPLEXITY FACTOR	0.4571
HULL WEIGHT	9,650 TONS
MACHINERY WEIGHT	1,400 TONS
ELECTRICAL WEIGHT	335 TONS
C & C WEIGHT	50 TONS
AUXILIARY WEIGHT	1,305 TONS
OUTFIT & FURN WEIGHT	1,960 TONS
LABOR RATE	$15/MH
LABOR OVERHEAD RATE	100%
MATERIAL OVERHEAD RATE	2%
PROFIT	10%

Table V. Sample preliminary design stage data input to the Parametric Module.

ITEM	**WEIGHT**	**MAN-HOURS**	**MATERIAL $**
HULL	9,650	220,114	$ 7,720,000
MACHINERY	1,400	27,364	28,015,000
ELECTRICAL	335	264,214	8,375,000
C & C WEIGHT	50	35,988	2,000,000
AUXILIARY	1,305	116,131	13,060,000
OUTFIT & FURN	1,960	412,774	19,605,000
LABOR TOTAL (man-hours)		1,076,584	
LABOR RATE		$15 / MH	
DIRECT COSTS		$16,148,760	$78,775,000
INDIRECT COSTS		$16,148,760	$ 1,575,500
PROFIT	$ 3,229,752	$ 8,035,050	
TOTAL PRICE		**$123,912,822**	

Table VI. Sample preliminary design cost estimate for a 45,900 ton RO/RO.

The same approach was used to derive SWBS-based ECERs for the preliminary and contract design stages. At these stages the information is likely to be available to estimate labor and material costs for all the SWBS groups. Table IV shows what the equations might look like at the one-digit SWBS level. These ECERs should not actually be used for estimates, but the different users of the PODAC Cost Model should use the forms of these ECERs along with their own cost data to develop their own solutions for these equations.

Using ECERs, the Navy or shipyards should be able to perform cost estimates in very little time with a minimum amount of data input. For example, at the concept stage, a customer might want to estimate the cost of a 45,900 ton RO/RO with a speed of 20.2 knots. A shipyard which has populated the PODAC Cost Model with their cost history could develop an estimate in a matter of minutes.

Many bids are prepared at the preliminary design stage, at which time more detailed information is available. To estimate the same RO/RO at the preliminary design stage, the information shown in Table V is typical input. Using this input and the sample equations shown earlier, an estimated price of $124 million is calculated, comprised of man-hour and material estimates as shown in Table VI.

The actual estimated cost for this ship depends on the ECERs developed using return cost from a user's specific database. In addition to using the PODAC Cost Model to tailor the ECERs, rather than using the OECD factors, a shipyard may wish to also develop their own complexity factors based on the various ship types produced in their yard.

<u>Product-Oriented ECERs</u>

The current version of the PODAC Cost Model includes only SWBS-based ECERs. However, the full capability of the PODAC Cost Model cannot be achieved without the development and use of ECERs for Interim Products. The IPT is currently working on developing such ECERs.

The Translation Module makes it possible to roll up return costs from the lowest level collected by a shipyard to determine the cost and cost drivers of higher level interim products, as shown in Figure 9. A shipyard can now use the PODAC Cost Model to develop their own ECERs for Interim Products. The IPT hopes to work with the shipyards this year to determine the forms of these process driven product-oriented equations.

<u>Direct CERs</u>

Direct CERs are production-based equations, in contrast to the product based equations of the Empirical CERs. A direct CER might be in the form of linear feet per hour for assembling and fitting, or square feet per hour for painting. Direct CERs are derived from one of three sources:

- from a single selected ship in the database (Calculated),
- from a set of selected ships in the database (Predictive), or
- manual input from the user (Manual).

Calculated CERs are derived directly from return costs from one ship in the database. Predictive CERs are developed using averaging or linear regression of Calculated CERs from a set of selected ships in the database to get a single equation. It is also possible to manually input CERs based on an individual user's assumptions, such as decreasing the Predictive CER by 20% due to an anticipated improvement in a shipyard's production process.

Risk Module

The purpose of the Risk Module is to provide an indication of the cost estimate uncertainty for a given ship design, a given shipyard, and a given construction schedule. The Risk Module is still evolving, but at the most fundamental level should include a cost prediction and a confidence level and probability distribution about the prediction. Currently the Risk Module uses an off-the-shelf statistical package to derive a shipyard's risk for meeting an estimate.

Traditionally, cost estimates have been point estimates which provide no information about probability of occurrence, or potential variance. Historical cost estimates and return cost data can be used to help assess the potential variance, or risk, of a new point estimate. Risk is usually defined as the square root of variance, or the standard deviation. With the PODAC Cost Model, a user can perform statistical analysis comparing historical cost estimates with actual cost returns to derive a probability distribution for a specific shipyard. This distribution can then be applied to a predicted cost to assess the uncertainty of the cost estimate.

The following example shows how the Risk Module works using an estimate for an interim product such as a block. Assuming that the model database has information on twelve similar type blocks, one would first compare the estimates and actual costs for these twelve blocks (VII).

If the PODAC Cost Model predicted a new point estimate of 2,030 man-hours for the block, then the Expected Actual Cost would be 2,010. This is derived using the following formulas:

$$\text{Expected Actual Cost} = (1 + \text{Mean}) \times \text{Estimate} \tag{1}$$
$$\text{Expected Actual Cost} = (1 - .01) \text{ X } 2{,}030 = 2{,}010 \tag{2}$$

There is a 50% probability that the Expected Actual Cost will be equal to or less than the derived value of 2,010 man-hours. Shipyard management may consider that it is too much of a risk to rely on this estimate and would prefer a higher degree of certainty around the estimate. The Risk Module employs an off-the-shelf statistical package, @Risk to derive the maximum estimates for different levels of risk. The data from Table VII can now be applied to derive a bell-shaped distribution profile.

Analysis of Historical Costs vs Estimates
(Labor Cost in Man-hours)

Block	Estimated Cost	Returned Cost	%Variance
1	2,975	2,903	-2.40%
2	2,888	2,808	-2.80%
3	2,755	2,763	0.30%
4	2,804	2,792	-0.40%
5	2,765	2,730	-1.30%
6	2,540	2,597	2.20%
7	2,523	2,586	2.50%
8	2,477	2,465	-0.50%
9	2,355	2,307	-2.00%
10	2,300	2,265	-1.50%
11	2,200	2,154	-2.10%
12	2,120	2,042	-3.70%
		Average Variance	-1.00%
		Standard Deviation	1.90%
		Maximum	2.50%
		Minimum	-3.70%

Table VII. Typical interim product block estimates versus actual costs

The program then performs Monte Carlo simulations to produce a range of certainty for the block estimate (Table VIII). The shipyard now has a better idea of which estimate they are comfortable going forward with based on the amount of risk they are willing to accept. Using a conservative range of 90% certainty, the estimate for the block would be 2,060 man-hours.

Schedule Module

Work will begin this year in developing this module to provide the Navy and shipbuilders with the ability to determine the lowest cost schedule. The Schedule Module will also aid in assessing the impact on cost of changes in construction schedule, sequence, and duration of shipbuilding activities. It is intended that the Schedule Module will be capable of importing schedule data from the shipyard's scheduling system. The Schedule Module itself may be a separate model such as a computer model with derived relationships or a simulation of the ship design and production process to develop relationships.

Analysis of New Estimate Based on Historic Performance to Estimate

New Block Estimate 2,030 man-hours

Percent Certainty	Cost Below
5.0	1,947
10.0	1,961
20.0	1,978
30.0	1,990
40.0	2,000
50.0	2,010
60.0	2,020
70.0	2,031
80.0	2,043
90.0	2,060
95.0	2,074
99.0	2,100
99.5	2,110

Table VIII. Range of Certainty for a Block Estimate

PODAC COST MODEL CAPABILITIES

A very powerful cost tool has been developed by integrating all the functions of the PODAC Cost Model. The PODAC Cost Model in its current state provides the following capabilities and benefits:

- Estimates ship cost based on how the ships are built;
- Estimates by product, process, and/or system;
- Electronically imports, aggregates, and stores return cost data;
- Automatically updates cost estimating relationships with this return cost data;
- Provides multiple views of costs by products or processes;
- Reduces the time and increases the accuracy of developing estimates for bids and production planning;
- Identifies cost drivers and their impacts so that designers can design ships which are easier and less costly to build; and
- Provides meaningful information for production process improvement.

FUTURE WORK

The PODAC Cost Model to date has focused on the design and production of ships. However, since the inception of this project, the Navy's emphasis has shifted from almost solely decreasing ship production costs to determining how to work with the shipyards to decrease overall Life Cycle Costs. The need has been identified for a model or set of models which can slice up the costs of a total ship program in many different ways to perform total life cycle trade-off analysis as well as provide multiple views (Figure 11) for other decisions.

The PODAC Cost Model IPT is researching existing efforts for developing Life Cycle Cost Models and hopes to integrate with these efforts.

In the near future, the PODAC IPT will be teaming with shipyards to evaluate and further refine the model. Empirical CER forms will be determined for interim products and the schedule and risk modules will be further developed. With the Navy and shipbuilding industry working together to make these improvements, the PODAC cost model will become an invaluable analysis tool in current and future acquisitions where shipbuilders will be involved in design development much earlier, and where more teaming among the shipbuilding and supporting industries may occur.

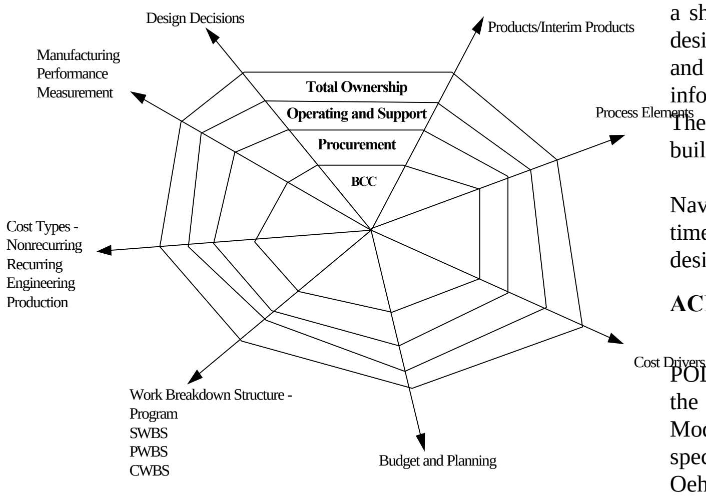


Figure 11. Multiple views of cost.

CONCLUSIONS

The PODAC Cost Model is much more than simply an estimating tool. The PODAC Cost Model stores and provides the information necessary for improving both the design and production of ships. Through use of the G/PWBS, the PODAC Cost model provides both a product view and a process view (Figure 12).

The product view provides information necessary for Navy and shipyard budgeting, planning, make-buy, and capital investment decisions. Knowing the cost of interim products helps the shipyards determine their most profitable product mix and teaming arrangements with other yards, vendors, and subcontractors. The product view is also applicable for bid preparation and evaluation, as well as for conducting ship performance trade-off studies.

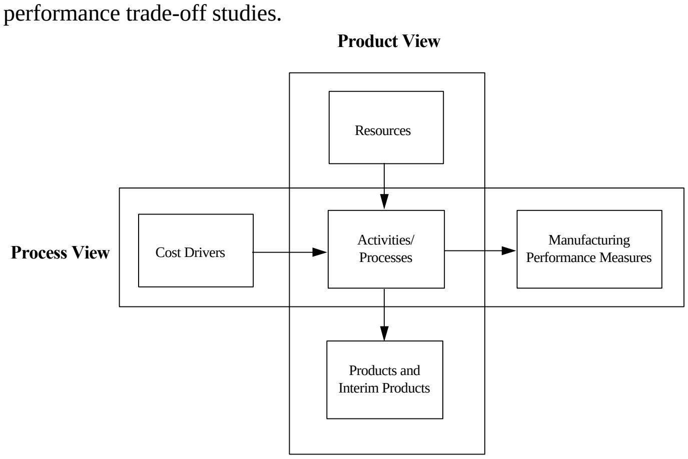


Figure 12. Product and process orientation of the PODAC Cost Model.

The process view is key for continuous improvement within both design and production. Understanding what the cost drivers are and how they affect the manufacturability and eventual cost of a ship or its products will help naval architects and designers to design more producible ships. The identification of cost drivers and performance measures provide the shipyards with the information necessary to perform process improvement studies. The ultimate application of the process view is to optimize the build strategy.

The product and process views together will enhance the Navy's and industy's ability to work together to provide accurate, timely, and meaningul cost feedback from cost analysts to ship designers and from production to design.

ACKNOWLEDGMENTS

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Particular appreciation is owed to Michael Wade of the Carderock Division/Naval Surface Warfare Center Shipbuilding Technology Department for initiating the PODAC Cost Model Project and for providing his encouragement, knowlege, and support to the IPT.

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Design, Fabrication, Installation, And Operation Of Titanium Seawater Piping Systems

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ABSTRACT

For many years, the U.S. Navy fleet has experienced severe corrosion and erosion problems in copper nickel seawater piping systems. Since titanium is extremely resistant to corrosion and erosion, it has been viewed as a potential solution to these problems. However, certain concerns regarding shipboard use of titanium needed to be addressed: marine fouling, galvanic action with other metals, welding, system fabrication in a normal shipyard environment, testing, and life cycle costs. Over a three year period, Ingalls Shipbuilding division of Litton Industries and the Naval Surface Warfare Center, White Oak, worked with various commercial equipment suppliers to address these concerns. Partially because of the success of this project, it was decided to retrofit titanium systems aboard TARAWA Class LHAs and to specify same for the new LPD 17 Class ships.

INTRODUCTION AND OBJECTIVES

Introduction

Navy shipboard copper nickel seawater piping systems have experienced severe corrosion, erosion, and marine growth blockage. This is evident from review of documented fleet failure data. Titanium has been used for many years on ocean oil drilling platforms and aboard merchant ships and foreign combatants for seawater piping systems and heat exchangers. The reasons for its use include its relatively light weight and extremely good resistance to corrosion and erosion. This history demonstrates that the use of titanium offers a potential solution to the Navy's problems. Titanium is more prone to adhesion of marine growth, and fabrication and installation of titanium piping systems have differentand more stringent requirements than copper nickel systems. Additionally, initial procurement costs are higher for titanium pipe, valves, and fittings. Over a three year period, Ingalls Shipbuilding and the Naval Surface Warfare Center, White Oak, worked with various commercial equipment suppliers to address these concerns. The purpose of the task was to address each of these issues so that the Navy could take advantage of titanium's unique ability to function effectively over the planned 40-year life of today's Navy ships.

Objectives

The objectives of this task were as follows:

1. Determine feasible and cost effective methods for preventing marine growth in shipboard titanium seawater piping systems;

2. Determine the impacts associated with fabrication and shipboard installation of titanium piping systems in a shipyard environment; and

3. Design an actual shipboard titanium seawater piping system and compare the performance and life cycle cost impacts associated with the use of titanium versus copper nickel for this system.

WATER TREATMENT

Overview of Various Fouling Control Methods

Since titanium is more prone to the formation of a surface layer of marine growth than the copper nickel piping systems it might replace, various available water treatment methods were reviewed.

Chlorine. The Navy is familiar with chlorine, having previously used it to purify shipboard potable water systems. In addition, the Navy has conducted extensive study of the use of chlorine for seawater purification. Electrolytic chlorinators are installed on various U.S. Navy piers. U.S. submarines, which have some titanium seawater system components, hook up to the chlorinators to clean out their systems between patrols. Chlorine is a relatively strong halogen that has a harmful effect upon the local marine environment when pumped overboard. Therefore, zero chlorine effluent may soon become required for U.S. waters.

Chlorine Dioxide. This chemical has an advantage over chlorine in treatment of one type of bacteria; but chlorine has the advantage in another area. However, it is still basically chlorine, relatively strong, and harmful to the marine environment. It would also be affected by the zero chlorine effluent requirement if that becomes the law.

Electron Beam Radiation. This method involves subjecting the incoming seawater to nuclear radiation. There are some factories in this country that use this method to purify their drinking water. Because of potential shipboard safety impacts and relative cost, this method was dropped from further consideration.

Bromine. This water treatment method is used throughout the fleet for potable water purification. Being weaker than chlorine, it might not be strong enough to effectively keep seawater piping systems clean. Conversely, although a weaker halogen than chlorine, it is still harmful to the marine environment.

Ultraviolet Light. Ultraviolet (UV) light treatment is used throughout the merchant fleets of the world, including the U.S., to purify potable water. It is allowed by the U.S. Coast Guard and the American Bureau of Shipping as an alternate to bromination. Many American municipalities use UV light treatment, sometimes together with ozonation, to purify drinking water and/or sewage. UV light is environmentally friendly. It is a method not yet used aboard U.S. Navy ships.

Ozone. Bubbling ozone (O_3) into drinking and/or sewage water is a common purification method, and was a probable by-product of the electro capacitance discharge technology experiment discussed in Reference [1]. Ozonation is also environmentally friendly. It is another method not yet used aboard U.S. Navy ships.

Based upon this review, UV light treatment and ozonation were selected for test evaluation and determination of effectiveness for shipboard seawater system purification.

Test System

Titanium Pipe Test Facility. A piping system design was prepared and various vendors agreed to supply components thereof. It was decided to install the proposed test equipment on one leg of a titanium pipe test facility already established in Ft. Lauderdale, Florida. This test facility was built to find solutions for Aegis cooling water system problems.

The original test loop was constructed in 1990. Seawater is pumped directly from the Port Everglades shipping channel, passed through a coarse duplex strainer with 4.76 millimeters (mm) (3/16 inch) hole diameter to filter out large shells and is then pumped at 19.2 liters/second and 8.4 kilograms per square centimeter (kg/cm^2) (300 gpm and 120 pounds per square inch, psi) through the test loop and discharged back into the channel. The loop was originally designed to test a variety of parameters including the effects of different flow rates on biofouling via piping legs of varying diameters incorporated into the titanium test loop to achieve flow velocities of 0.9, 2.4, and greater than 3 meters per second (m/sec) (3, 8, and greater than 10 ft/sec). A blank-off and stagnant leg, with a cruciform piping configuration to allow for observation of undisturbed stagnant seawater, were also part of the original installation. A new test and evaluation plan was drawn up and formalized via a Cooperative Research and Development Agreement (CRADA).

Equipment Supply. Several organizations participated in this new test effort by supplying various equipment. A list of those participants and equipment is contained in Table I.

It was originally planned to fabricate a copper nickel and bronze piping system which would be a mirror image of the already installed titanium piping system. The copper nickel system would be mirror image of the already installed titanium piping system. The copper nickel system would be connected to the titanium system and, with seawater flowing through both, comparative analysis of marine fouling rates could be made and the effectiveness of alternative water treatment methods could be determined. Due to revised priorities, this plan was put on hold. An existing copper nickel system at the shipyard was disassembled and shipped

TABLE I. PROJECT PARTICIPANTS.

ORGANIZATION	EQUIPMENT
ALFA-LAVAL MARINE & POWER	TITANIUM PLATE HEAT EXCHANGER
ASTRO METALLURGICAL	SOME PIPE CUTTING AND FLARING
DOBSON'S USA, INC./AQUAFINE CORP.	ULTRAVIOLET PURIFIER
DRESSER INDUSTRIES	COMPOSITE VALVES
EMERY TRAILIGAZ	OZONE GENERATOR
NAVAL SURFACE WARFARE CENTER CARDEROCK DIV., ANNAPOLIS CORPORATION	TITANIUM SHELL & TUBE HEAT EXCHANGER
OREGON METALLURGICAL CORPORATION	TITANIUM PLATE & PIPE SAMPLES
SPECIALTY PLASTICS, INC.	FIBERGLASS PIPE & FITTINGS
TITANIUM METALS CORP. (TIMET)	TITANIUM PIPE

to the test site as a substitute. It had previously been used for some flowing seawater tests. Although not a mirror image of the titanium system, it was believed that the system would still be useful for comparative analysis.

It was decided to install some fiberglass reinforced plastic (FRP) in the titanium portion of the system to evaluate its performance. Therefore, FRP fittings were retained for all the required elbows, tees, and reducing fittings. Composite valves for all the check, isolation, and sampling valves were included in the system design. Figure 1 depicts the final system design configuration.

It was originally planned to provide titanium flanges with stub ends to weld to the titanium pipe. However, sliding, rotatable flanges would allow more flexibility in system fabrication. Therefore, since the flanges would not see any of the seawater flowing inside the titanium pipe, the use of stainless steel sliding flanges was adopted as the most cost effective alternative.

System Fabrication. Receipt of all the system components at the test site was completed. The coolers and seawater treatment equipment were connected to the supply main via the fiberglass valves and fittings. Since the total connected length of FRP valves and fittings formed a subsystem sufficient for evaluation, no straight sections of FRP pipe were installed. It was therefore decided to utilize the FRP pipe already received for future piping system evaluation at the test site.

The requisite lengths of titanium pipe necessary for completion of the system were determined, cut to the proper lengths, fit with stainless steel sliding flanges, and flared. The finished pipes were connected into the test loops, completing system fabrication. Figures 2 through 7 show the completed installation. Please refer to the Acknowledgments for a complete list of project participants.

System Testing. Successful system lightoff was accomplished on 14 April 1993, with the assistance of representatives from the various equipment suppliers.

Some operational problems were experienced:

1. Backup of water into the ozone generator occurred, but this was resolved by installing a small check valve in the ozone supply tubing.

2. The ambient humidity in the area was so high that the single tower, nonregenerative air dryer became saturated within 24 hours, causing ingestion of excess moisture by the ozone generator. This problem was resolved by replacing the dryer with a two tower regenerative unit.

3. The site was hit by lightning, knocking out both the ozone generator and the UV purifier, in addition to other nonrelated equipment at the facility. The damaged equipment was repaired and put back on line.

4. The system supply pump failed several times and was eventually replaced.

5. Replacement of a nearby navigational aid required that the system be shut down because of the aid's proximity to the system's supply inlet. Operation of the system during installation would have posed a safety hazard to the divers installing the aid and would also have caused an abnormal ingestion of debris into the system.
6. At one point, excessive barnacle encrustation of the system's sea suction basket severely reduced flow performance until the basket was cleaned.

7. Installation of other buildings and support services nearby at the facility caused further disruption and temporary curtailment of operations.

Water Analysis. When the equipment problems were

resolved, the water analysis test plan was accomplished as listed below.

1. Ten days running treated, with daily water samples taken for analysis. The UV&O_3 subsystems were both operated at the same time.

2. Open and inspect for marine growth, corrosion, and erosion.

3. Ten days running untreated, with daily water samples taken for analysis.

4. Open and inspect for marine growth, corrosion, and erosion.

5. During both treated and untreated tests, take water samples, let remain stagnant up to ten days, and analyze.

Local personnel at the test site took the water samples, performed the initial analyses required (such as oxygen and ozone content, turbidity, and temperature); packed the samples in dry ice; and shipped them to marine laboratories fo rmore in-depth analysis. Marine and/or micro boilogists conducted the detailed water anslyses showed that UV purification and ozonation significantly reduced colony forming marine organisms in titanium and fiberglass seawater piping systems. Detailed results are contained in the final report, Reference[2].

Open and Inspect Examinations of the Titanium Test Loop. Light biofouling (a matrix of microbial growth and a few macrofouling organisms) and what appeared to be a layer of sand/sediment on the "Y" area was observed during the open and inspect examination. The mineralogical deposits with microbial biofilm could be wiped off easily by hand and the titanium pipe surface showed no discoloration or under-deposit pitting. The titanium plate heat exchanger ws also opened and inspected. No macrofouling was observed after 10 days of untreated seawater running through the titanium plate heat exchanger.

UV and O_3 Lessons Learned. The UV purifier apparatus operated more reliably than the ozone generator, with much less maintenance downtime. Another drawback associated with the operation of the ozone generator involved the requirement for more support services. Both the UV and the ozone units required an electrical power source; however, the ozone unit also required fresh water cooling and a supply of clean, dry air. The manufacturer advised that either compressed oxygen cylinders or an air compressor with dryer would suffice. A compressor and a deliquescent dryer were therefore connected to the air supply

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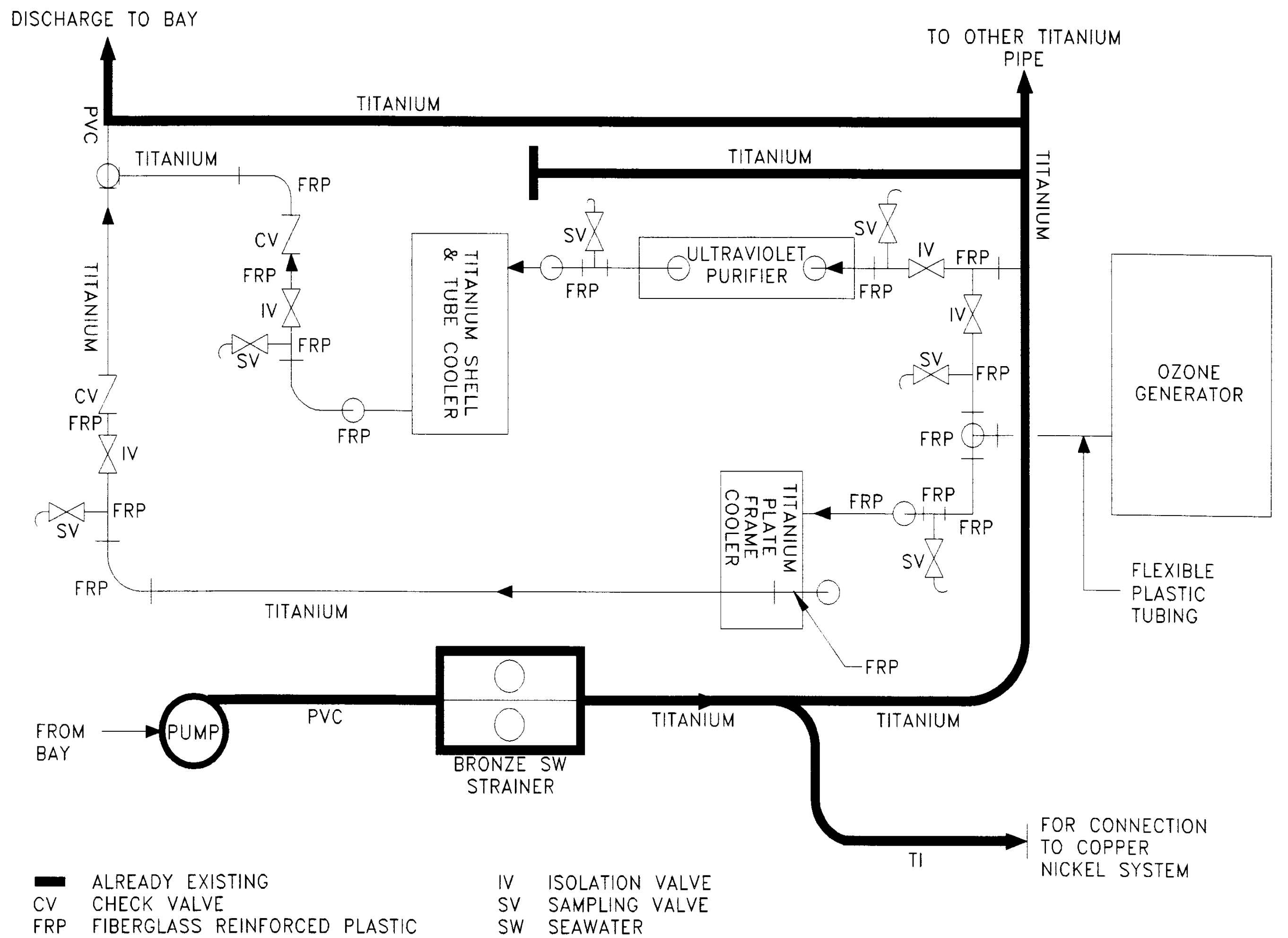
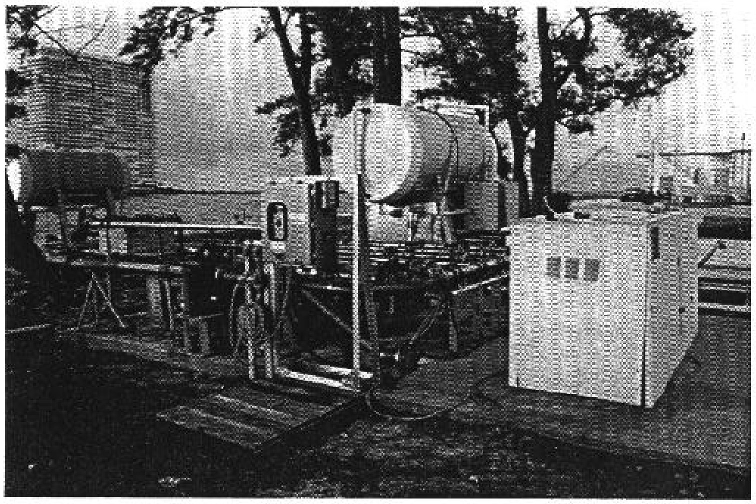


Figure 1. Test Equipment Arrangement Sketch

Figure 2. Ozone generator in white box on right.
UV purifier control panel in center.



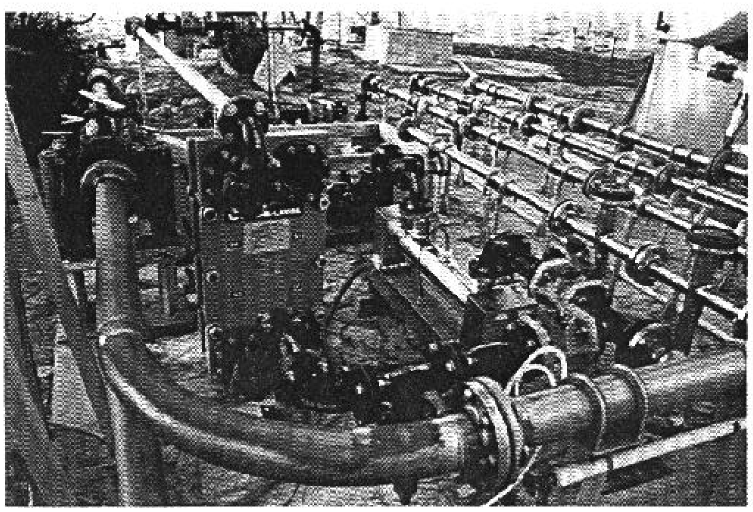


Figure 3. Left to right:
Duplex strainer in SW supply main, Titanium plate &
frame cooler, UV purifier.

NSWC
Naval Surface Warfare Center
DAHLGREN DIVISION

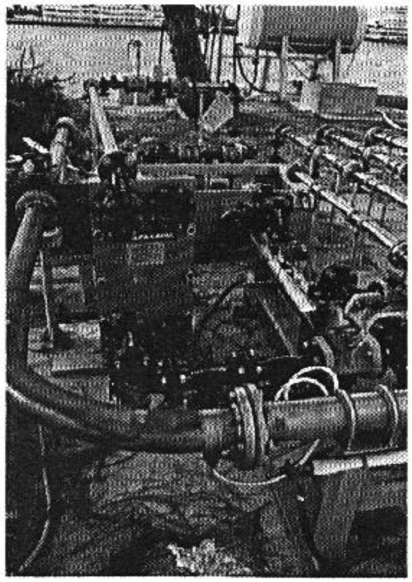


Figure 4. Alfa-Laval titanium plate & frame cooler.

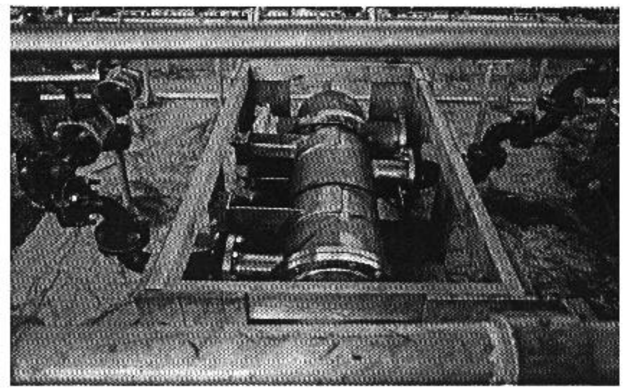
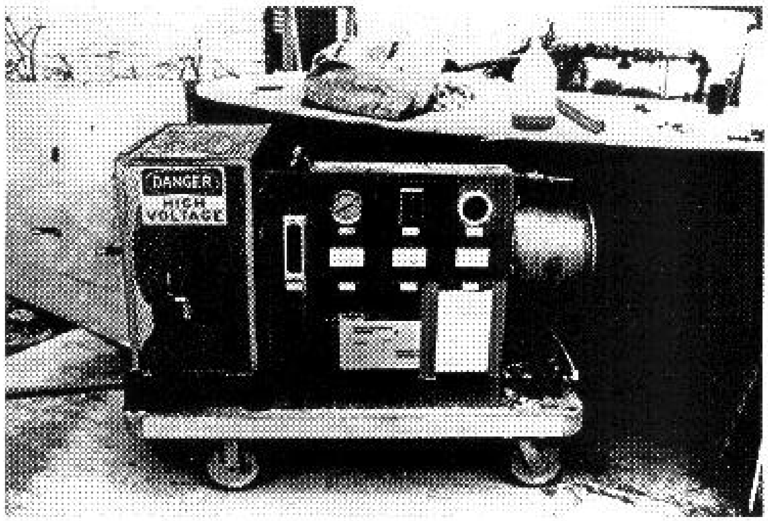


Figure 5. NSWC titanium shell & tube cooler.

Figure 6. Emery Trailigaz Ozone Generator.



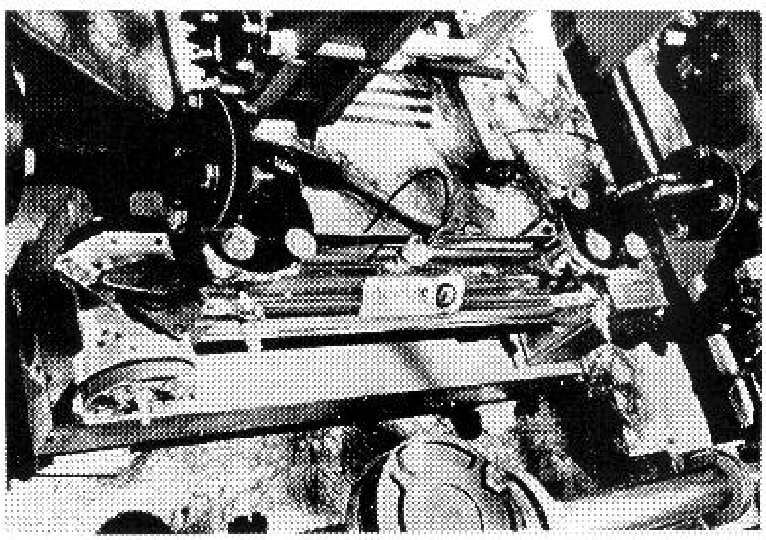


Figure 7. Aquafine Ultraviolet Purifier.

Due to the extremely humid ambient conditions in the area, the deliquescent medium became saturated too frequently, requiring replacement. Therefore, the dryer was replaced with a self regenerative, dual tower desiccant unit. That type of dryer operates by using one tower for drying the air supply, while the second tower is being dried via a small portion of the dry air from the first tower. The functions of the two towers are automatically switched via a timing mechanism.

Ozone generators produce ozone via high voltage (33,000 volts) discharge across glass or synthetic crystal tubes, which have a dielectric constant compatible with the process. UV purifiers kill microorganisms by shining ultraviolet rays across similar glass or crystal tubes through which water is flowing. Either of these apparati would probably be acceptable for pierside use. However, the ozone generator manufacturer requested that the unit be protected from the elements. Therefore, a plywood box was used at the test site to house the apparatus, as shown in Figure 2. The UV apparatus, including the purifier and its control panel, shown in Figures 2 and 3, did not require any special protection from the elements.

For shipboard shock survivability, it is recommended that:

1. The stronger, less brittle synthetic crystal tubes would be preferable to glass.

2. The tubes should be soft mounted, rather than their present land-based hard mounted configuration.

3. This might be accomplished via employment of synthetic rubber mounts at the ends of each tube.

In regards to size and weight, the UV purifier was much lighter in weight and occupied much less space. In regards to shipboard operating personnel safety, the ozone generator produces much higher voltage than the UV purifier. Note the warning label plate on the ozone unit shown in Figure 6.

Because of the superior reliability demonstrated by the UV purifier unit and the other considerations discussed above, at the conclusion of the project testing, the UV purifier was kept on line but the ozone generator was sent back to the manufacturer. Further comparative testing of UV purification is planned at another test facility in King's Bay, Georgia, and the UV equipment manufacturer has agreed to provide a unit for that testing. Chlorination is currently being tested at that facility. However, it is expected that the Environmental Protection Agency (EPA) will soon forbid discharge of any chlorine into U.S. harbors; so UV purification is seen as a promising alternate and environmentally friendly water treatment method.

Composite Components' Performance. The composite valves and fittings tested exhibited no indications of corrosion. No conclusions can be drawn, however, regarding erosion resistance because of the relatively short period of testing.

The composite valves were installed without any exterior protective coating. As a result, the yellow valve surfaces were bleached to a much lighter color within a few months. Discussion with the manufacturer verified that this might be attributed to ultraviolet light from the sun causing an embrittlement of the surface layers of the valve. This could be prevented by application of a protective coating (paint) or by impregnating the composite material with other substances. For instance, the fiberglass tees and elbows installed in the system were impregnated with carbon black to absorb ultraviolet rays. The carbon black distributes the absorbed energy throughout the material. This prevents an excessive rise in the pipe's surface temperature which would cause vaporization of the resin that holds the glass together. Therefore, protective coatings or impregnation would be required for weather deck applications of composite, specifically fiberglass, piping components installed aboard ships.

SHIPYARD FABRICATION

Previous Effort

A Titanium Applications Seminar was held at Ingalls' shipyard in January 1991. The meeting was well attended by representatives of the Titanium Development Association (TDA); Naval Surface Warfare Center (NSWC), White Oak; Naval Ship Weapon Systems Engineering Station (NSWSES), Port Hueneme; Supervisor of Shipbuilding, Conversion and Repair (SUPSHIP), Pascagoula; and various concerned shipyard departments. It was concluded that the shipyard had adequate equipment and personnel to successfully fabricate and install titanium piping systems aboard ships.

Later, one TDA member company provided some titanium plate and pipe samples. The plates were delivered to the shipyard welding laboratory, where they were successfully cut, bent, drilled, and welded by shipyard personnel.

Commercially Pure Titanium. Bending: A 3.2 mm (1/8 inch) thick piece was bent to a radius of 6.4 mm (1/4 inch) and 19.1 mm (3/4 inch). Both bends were successful with no indication of cracking.

Drilling: A 6.4 mm (1/4 inch) diameter hole was drilled with no difficulty.

Thermal Cutting: A 6.4 mm (1/4 inch) thick piece was cut with both oxy-acetylene and plasma processes. Both processes made acceptable cuts. Because of the speed of cutting, it was difficult to perform manually. The cut edges were heavily oxidized.

Welding: A butt weld was made in an 3.2 mm (1/8 inch) thick plate. Gas tungsten arc welding using Ti-1 wire was utilized. There was no apparent problem with this welding.

Alloy Titanium (6AL-4V). Bending: A 3.2 mm (1/8 inch) plate was bent to a 19.1 mm (3/4 inch) radius with no cracking but with a large amount of springback. A 3.2 mm (1/8 inch) plate was used to attempt to make a 6.4 mm (1/4 inch) radius bend but the material failed brittlely.

Drilling: A 6.4 mm (1/4 inch) diameter hole was drilled with no difficulty.

Thermal Cutting: A 6.4 mm (1/4 inch) plate was cut using oxy-acetylene and plasma processes. As with the CP titanium, both processes will cut the material but the required speeds make manual cutting difficult. Again, the edges were heavily oxidized.

Welding: A butt weld was made in a 3.2 mm (1/8 inch) plate using gas tungsten arc and 6AL-4V wire. A crack developed in the weld. This was attributed to welding over

remnant oxides on the cut edges. Because of material availability, a 1.6 mm (1/16 inch) plate was welded and this was successful.

Lessons Learned. Both types of titanium alloys can be processed using shipyard processes. The commercially pure titanium is easier to fabricate and would be the recommended choice for shipboard use.

It was therefore determined that the welding laboratory had all the capability necessary to fabricate grade 2 titanium plates and shapes. This is the "commercially pure" grade installed at the test site and recommended for most shipboard seawater piping systems. Shipboard seawater coolers would require a different grade of titanium alloy, such as the 6AL-4V, which has better heat transfer characteristics.

The 25.4 mm (1 inch) diameter pipe segments were delivered to the shipyard's pipe shop. After bending several segments, pipe shop personnel observed that the thin wall titanium pipe had more springback than the copper nickel or corrosion-resistant (stainless) steel (CRES) they normally dealt with. For instance, using one straight section of titanium pipe, they attempted to form a 127.0 mm (5 inch) radius 90 degree bend. Even though the pipe was initially bent by the bending machine to 114 degrees, when released from restraint, it sprang back to less than 90 degrees. It was determined that the pipe had to be bent to 132 degrees before it would spring back to produce a 90 degree bend with that radius. As long as the springback property was known, the bending machine could be set to compensate for it. This showed that the shipbuilder could perform hot and cold work on titanium plate and pipe in a shipyard environment.

Test Site Supply Main

The test site's 101.6 mm (4 inch) supply main, from the feed pump to the seawater duplex strainer, was composed of polyvinyl chloride (PVC). The test site personnel wanted to change the material to titanium, so that the system would be uniform and to stop leaks. The shipyard volunteered to purchase the materials, fabricate the pipe segment, and ship it to the test site. This would serve the dual purpose of proving that a shipyard has the capability to fabricate titanium piping systems in a shipyard environment and providing the test site with a desired product. Refer to Figure 8 for a drawing of this pipe configuration.

Welding. A proper titanium weld is indicated by the finished weld exhibiting a silver color on the surface. In decreasing order of acceptability, the following chart applies.

Acceptance Criteria

Silver - most acceptable
Light or dark straw (gold) - acceptable
Light blue - marginal
Dark blue - reject
White or gray - completely unacceptable

This is one advantage unique to welding titanium. The very color of the finished weld gives an indication of the quality of the weld. The other normal shipyard materials - such as copper, nickel, bronze, carbon steel, mild steel, stainless steel, HY-80 steel, and aluminum - do not exhibit such easily discernible indications.

It took about two weeks to train a shipyard welder in the proper methods for working with titanium. Some difficulties were experienced with his first attempts at qualification, when he butt welded two pieces of 101.6 mm (4 inch) pipe together. He was welding scrap pieces of the subschedule 5, grade 2 pipe which would be used to fabricate the supply main. The welder's first attempts produced welds with a blue color and some that were powdery white, both being unacceptable. Further welds produced a more acceptable color, but x-rays showed impurities in the weld.

The following corrective actions were taken:

1. Since the faulty welding had taken place in a large open area subjected to stray drafts, a small enclosed booth was fabricated of clear plastic sheets. Welding within this booth prevented relatively cool ambient air from blowing across the hot titanium welds.

2. Because the larger of the two diameters of welding rods had been employed, it took longer for the weld to heat up; but it also took longer to cool down below the 316°C (600°F) threshold temperature required to prevent embrittlement. Therefore, the smaller diameter weld rod was used for subsequent operations.

3. The welding shield at the tip of the rod was enlarged, so that inert gas would be held in place over the hot weld for a longer period of time - until the weld cooled to less than 316°C (600°F).

Taking these measures resulted in a silvery weld surface, which also exhibited no impurities when x-rayed. The welder was therefore qualified and subsequently certified by SUPSHIP, Pascagoula.

Bending. The supply main piping system was to be fabricated from three 4-inch segments which were each 6.1 m (20 feet) long. The finished product would be about 15.2 m (50 feet) long, with an S-bend near one end. To form the S-bend, the pipe was fed into an electrohydraulic bending machine, after insertion of a mandrel with 3 balls, widely spaced. Unfortunately, the pipe formed surface ripples along the inside of the bend. There were ripples for about 25.4 mm (4 inches), followed by about 25.4 mm (4 inches) of smooth pipe surface, followed by about 25.4 mm (4 inches) of ripples, etc. Each ripple was about 3.2 to 6.4 mm (1/8 to 1/4 inchs) deep.

A tool manufacturer recommended that the mandrel be replaced with one having more balls, more closely spaced. This would give more support to the inside surface of the pipe, to help prevent buckling. To support the outside surface, it was recommended that a wiper dye be used. This is a convex surfaced tool that is placed on the machine just before the pipe feeds into the big pulley wheel, prior to bending. See Figures 9 and 10 for more details on mandrels and wiper dyes.

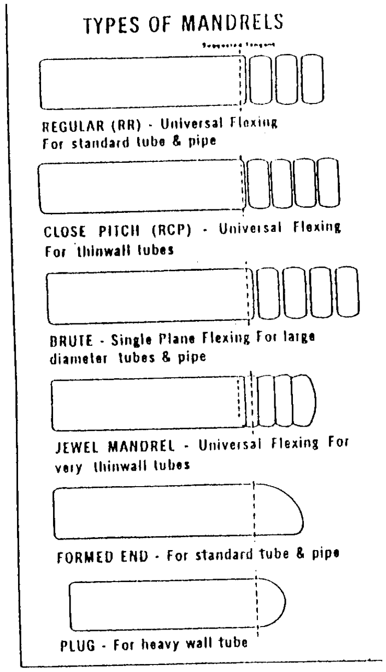
A new section of pipe was put onto the machine; a

mandrel having 5 more closely spaced balls was inserted into the pipe; and a wiper dye installed just before the pulley. These measures resulted in a smooth S-bend, with no deformities.

Fabrication. As previously stated, the test facility preferred sliding flanges, in order to allow more flexibility in system alignment. Therefore, titanium flared end fittings were purchased to weld to each end of the five pipe sections. Stainless steel flanges were installed. Galvanic action was not expected because the flanges were on the outside. The qualified welder slipped the flanges onto each section and successfully welded the flared end fittings in place.

Hydro Testing. The finished pipe sections were bolted together and the complete assembly was then hydrostatically tested to 15.7 kg/cm^2 (225 psi) for 30 minutes, twice as long as the normal requirement. The pressure was taken as 1.5 times the maximum seawater system operating pressure aboard TICONDEROGA Class cruisers: the firemain pressure of 10.6 kg/cm^2 (150 psi). No leaks were detected, except for a few drops at one of the gasketed connections. This was probably due to those bolts not being tightened quite enough.

Installation. The main was disassembled and reassembled at the test facility where the system has been operating successfully for three years.



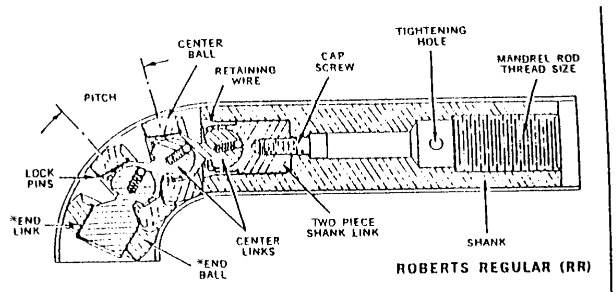


Figure 9. Mandrels

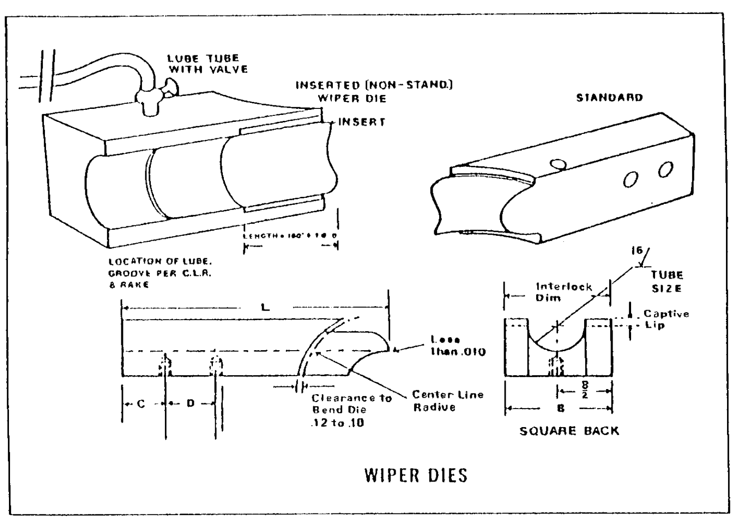


Figure 10. Wiper Dies.

PROTOTYPE SHIPBOARD SYSTEM DESIGN & COST ANALYSIS

Cruiser Design

The Navy AEGIS Program Manager for cruisers and destroyers requested that a prototype aboard an AEGIS cruiser or destroyer. After review of the available failure data for all AEGIS cruisers commissioned since 1983, the forward AEGIS cooling water system, being small and relatively independent, was selected for titanium retrofit. Accordingly, a proposal was prepared and submitted for installing this system aboard CG 73, PORT ROYAL, the last AEGIS cruiser to be built. This proposal was eventually rejected because the cruiser construction program was nearing completion.

Destroyer Design

The next major class of surface combatant under construction was the Aegis destroyer. Review of failure data revealed that the gas turbine generator (GTG) seawater cooling systems were also prone to failure. Since those systems aboard the destroyer are independent, they were selected as design candidates for replacing copper nickel components with titanium.

Piping and flow were redesigned to make optimum use of the advantages inherent in the use of titanium.

The common fix currently employed to remedy leaking 90/10 seawater piping systems involves replacing with 70/30. The 70/30 is a little stronger than 90/10, but is still relatively soft compared with titanium. The shipyard conducted a comparative analysis of pipe acquisition costs: grade 2 titanium versus 90/10 and 70/30 copper nickel. Table II indicates that titanium is about 50 percent more expensive than 90/10 and was equal to or less than 70/30. Titanium once installed should last the projected 40 year life of each ship. As indicated by review of fleet failure data, copper nickel seawater piping system failures are not rare. If copper nickel has to be replaced even once, the titanium pays for itself. Therefore, titanium seawater piping systems would be more life cycle cost effective.

The seawater system design velocity could be increased over the destroyer's currently specified upper limit for copper nickel, 3.6 mps (12 feet per second, fps), because of titanium's superior abrasion resistance. The AEGIS cruiser's seawater systems were designed with a 4.5 mps (15 fps) upper limit. Therefore, the destroyer's allowable velocity was raised from 3.6 to 4.5 mps (12 to 15 fps). The Navy personnel associated with ship noise signatures indicated that the resultant increase in noise generated would be within acceptable limits. One advantage to be gained from increased velocity is decreased proliferation of marine growth on the pipe walls. This may mitigate the necessity for water treatment.

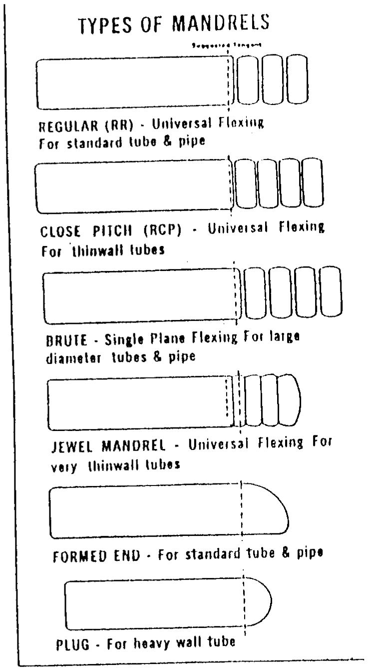
This increase in velocity allowed decreasing the pipe size from 63.5 to 50.8 mm (2-1/2 to 2 inches), making the titanium system more cost effective.

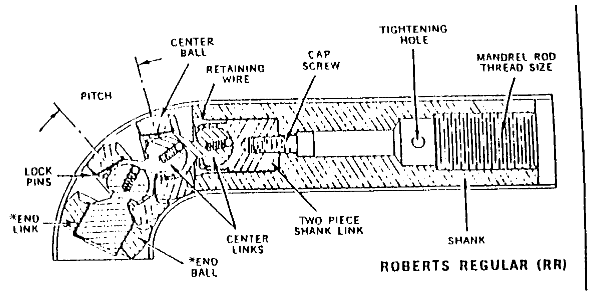
Retention of bronze valves also improved cost effectiveness. Titanium ball valves made in the United States cost about 10 times the price of bronze valves. During a recent trip to Norway, it was determined that titanium valves there were about 3 times more expensive vice 10.

A gas turbine propelled patrol boat, the HIDDENSEE, was built in Russia in 1985 for the East German Navy. When East and West Germany united, the boat was given to the U.S. Navy. Titanium seawater piping systems with bronze valves were part of the design. To prevent galvanic corrosion of the bronze by the titanium pipe, the Russians had inserted composite gaskets, bolt sleeves, and washers at the appropriate interfaces. Examination of the valves determined that, if the valves were those originally installed, they had weathered nine years of operation without deterioration.

Retention of bronze valves would decrease system acquisition cost without seriously degrading long term system operation. Bronze valves last much longer than copper nickel pipe. Composite gaskets were therefore incorporated into the AEGIS destroyer's GTG titanium cooling water system design. This would include any interface with a dissimilar metal: cross connect with the firemain, bronze valves, sea chest, overboard discharge, etc. The Navy will use these gaskets in titanium systems which they plan to install aboard other ship classes, as discussed in the next section.

Again to improve system cost effectiveness, it was decided to retain the bronze and copper nickel system components within the GTG module. The GTG manufacturer was apprised of these intentions, and it was left up to them to decide whether to change their part of the system to titanium. Their subsystem includes three copper nickel and bronze shell and tube


TYPES OF MANDRELS
REGULAR (RR) - Universal Flexing
For standard tube & pipe
CLOSE PITCH (RCP) - Universal Flexing
For thinwall tubes
BRUTE - Single Plane Flexing For large
diameter tubes & pipe
JEWEL MANDREL - Universal Flexing For
very thinwall tubes
FORMED END - For standard tube & pipe
PLUG - For heavy wall tube


TIGHTENING
HOLE
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MANDREL ROD
THREAD SIZE
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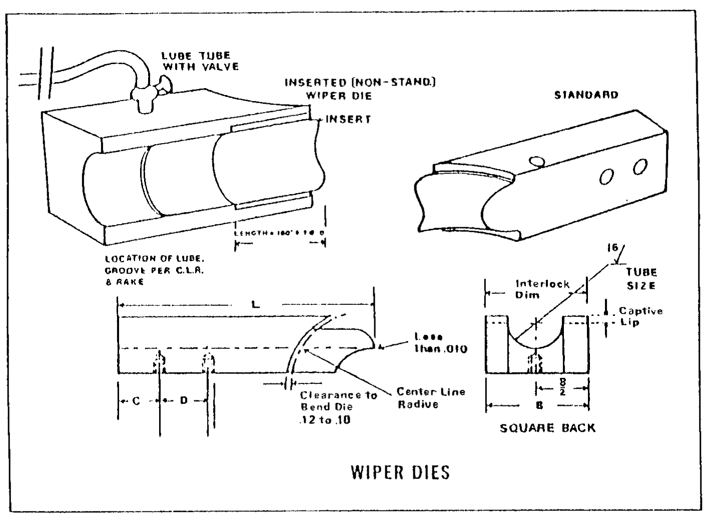
ROBERTS REGULAR (RR)


LUBE TUBE
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.12 to .10
Center Line
Radius
Interlock
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TUBE
SIZE
Captive
Lip
B
SQUARE BACK
WIPER DIES

type coolers. If they eventually opt for titanium, it is hoped they will change to plate and frame units which are less maintenance intensive (easier to clean and to determine when clean) and are usually smaller and lighter in weight. They are also comparable in cost to the older type of shell and tube coolers.

The piping wall thickness was decreased due to titanium's superior strength. This will decrease system weight and increase ease of installation. Pump characteristics were revised as necessary to accommodate the change in flow. Titanium pumps would be used, if available, for compatibility and decreased weight. If titanium units were not available, composite gaskets would be added.

A rough order of magnitude (ROM) price was estimated for the proposal, based upon material and labor impacts associated with new construction, for a Flight IIA AEGIS destroyer. Although the titanium equipment acquisition costs would exceed that of the copper nickel and bronze equipment originally specified, the ship's life cycle costs would be greatly reduced because the titanium would last longer than the 40 year design life of the ship.

Subsequent Developments

The shipyard met with the Navy and some titanium manufacturers to help determine whether it was practical to retrofit some titanium seawater piping systems aboard the LHA Class during overhaul, and aboard the new LPD 17 Class during construction. It was decided that both plans were practical and cost effective and are now proceeding accordingly. USS SAIPAN, LHA 2, was retrofit with titanium piping systems. Titanium piping systems were also included in the shipbuilding specifications for LPD 17.

Pierside chlorinators are installed at various submarine bases for cleaning seawater systems between patrols. The Seawolf Class submarines have electrolytic chlorinators installed aboard ship. Some submarines currently in service have titanium coolers, but the interconnecting piping systems are Inconel 625, which is more expensive than titanium. Also, Inconel 625 is subject to stress corrosion cracking under these conditions, whereas titanium is not.

Marine organisms in seawater attach themselves to the walls of copper nickel pipe via excretion of an acidic solution. This solution reacts with the metal to create a small pit in which the organisms reside. This also sets up a galvanic couple between the surface beneath the organisms and the still intact protective film on the metal surface just outside the colony. This causes corrosion of the metal surface beneath the colony, deepening the pit. Thus originates the term microbiologically influenced corrosion (MIC). This phenomenon was studied in research projects described in References 3 through 9.

However, since titanium is resistant to almost all acidic attack, marine organisms can only attach themselves to a surface layer of green slime, if one has formed. When water flow through the pipe is started or increased, these organisms are frequently washed away. Therefore, titanium seawater systems will remain cleaner than copper nickel systems, especially at higher allowable flows.

At another meeting, it was stated that rules and regulations would be formulated for titanium fabrication; that any shipyard wishing to fabricate titanium systems or structure for a Navy contract would be visited; and the acceptability of the shipyard's facilities, training, safety, and operational procedures would be determined. It was also decided that, for future ship classes and for retrofit, chlorinators would be installed to prevent marine fouling; and dechlorinators would be installed upstream of overboard discharge fittings to prevent adverse environmental impact.

CONCLUSIONS

Copper nickel seawater piping systems exhibit failures due to erosion and corrosion mechanisms in time frames as small as one year, depending on service.

Cost analysis indicates the following.

1. Titanium pipe prices are about 50 percent greater than 90/10 copper nickel and equal to or less than 70/30 copper nickel.

2. Titanium valves currently cost from 3 to 10 times more than bronze valves.

3. Based upon the copper nickel seawater piping system failure rates reported, utilization of titanium pipe and fittings, with retention of bronze valves, should provide a more cost effective system over the projected 40 year ship life. This assumes a cost effective method to prevent galvanic action between the titanium and nontitanium system components.

Based upon titanium's properties and its use aboard offshore oil rigs in heat exchangers aboard merchant ships, and aboard foreign combatants, it is predicted that titanium seawater piping systems will last the 40 year projected life of U.S. Navy ships.

Use of composite gaskets, bolt sleeves, and washers may be an effective isolation method to prevent galvanic corrosion of nontitanium components of titanium seawater piping systems.

Titanium seawater piping systems can be successfully fabricated in a normal shipyard environment, provided the welding is performed in a draft-free area by a qualified welder.

Ultraviolet radiation and ozone generation are effective, environmentally friendly methods for reducing marine fouling of seawater piping systems. Based upon the equipment tested and the time period involved, ultraviolet radiation equipment appears to be more reliable, safer, lighter weight, smaller, and require fewer support services than ozone generation. Additional evaluation would be warranted, for both water treatment techniques, to determine associated shipboard and/or pierside impacts; these would include both material and labor impacts associated with installation, operation, maintenance, and spare parts inventory. This would determine the long term cost effectiveness of these seawater treatment methods compared with chlorination/dechlorination.

Nonmetallic composite materials installed on ships' weather decks would require a protective coating and/or impregnation to prevent deterioration due to ultraviolet radiation

from the sun.

The Navy and private industry do successfully cooperate in testing programs geared to the improvement of ship design, construction, operation, and maintenance.

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An Integrated Steel Workshop For Shipbuilding: A Real Application Of Automation

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ABSTRACT

The paper describes the layout of an innovative automated steel workshop for the manufacturing of ship blocks, recently set up at Fincantieri's Monfalcone shipyard. The system implements the results of a European EUREKA! Research program called FASP - Flexible Automation in Ship Prefabrication.

The various working areas of the shop are described; for each of the new technologies being applied, the level of automation and integration with the other areas is discussed; the advantages obtained are compared with the best typical standards of a traditional production workshop.

Inside a fully automated workshop, the information support must have a high integration and flexibility level.
The two main issues relevant to information technology are described, i.e.:

- *the modular and integrated systems for the design, part program generation and trasmission; and*
- *the production programming, management and control system.*

GENERALITY

The prefabrication workshop is the area of the yard that generally offers the greatest opportunities to achieve efficiency increases through the introduction of automation and the application of innovative technologies in search of improved competitiveness, cutting costs and shorter manufacturing lead time.
Such an approach is based on the following issues.

- Most of the production process has traditionally been based on methods contemplating manual activities. The exploitation of just low-to-medium levels of automation reduce time-consuming and labor intensive exercises, especially considering the necessary minute adjustments and remakes.
- Improved accuracy in the process can be achieved at different stages of prefabrication by resorting to automated systems of a higher sophistication while limiting or eliminating manual operations. The accuracy of blocks obtained with such solutions, results in substantial savings in terms of labor and time needed in the downstream assembly and outfitting operations.
- A smoother running management of lines and areas can thus be achieved allowing for a steady, unbroken production flow, substantially easier planning routines and reduced intermediate storage periods.

Bearing in mind these considerations; with the aim of obtaining a man-hour cut of 50% during prefabrication; and a reduction of 1 to 2 months in building lead time, Fincantieri set up the FASP research project in 1989 - the acronym stands for "Flexible Automation in Ship Prefabrication" -.

The target was to study, develop and set up a demonstration model of a prefabrication workshop at Fincantieri Monfalcone shipyard, the Company's largest. The model features automated robotized lines/areas, fully integrated with the CAD-CAM system and the Production Control System. This concept, as translated into reality on the production floor, is able to handle the production of different structural members of different type and size, making it possible to build ships of very different structural characteristics, at the same level of efficiency and quality. The research covered not only hull construction but also hull design, production planning, monitoring and management.

The technologies and methodologies, whose application within the prefabrication activities were considered in the program, are:

- robot application,
- laser cutting and welding,
- off-line programming,
- production simulation,
- automatic bending systems,
- parts marking and automatic tracking,
- parts handling with manipulators,
- on line quality control,
- telemetry for the verification of the manufactured products,
- advanced sensors application,
- visual and image processing systems, and
- control techniques of deformation due to thermal stress.

The main techniques for the implementation of a Computer Integrated Manufacturing system have also been analyzed within the research program.

THE RESEARCH ORGANIZATION

The schedule called for a 6-year term, ending 1995. Partners of FINCANTIERI, FASP project leader, were:

- ANSALDO, an Italian electro-mechanical group;
- ASTILLEROS ESPAÑOLES, a Spanish shipbuilder;
- ENEA, (Ente per le Nuove tecnologie, l'Energia e l'Ambiente), an Italian research committee;
- IGM Robotersysteme AG, an Austrian robot welding company; and
- SOLVING, a Finnish air cushion transportation group.

The research project period was organized in three phases.

Phase 1: Study, planning and design of the reference model.

Phase 2: Design and on-site testing of the critical processes and relevant technologies.

Phase 3: Construction of the prototype prefabrication workshop to measure up with the original target of the project.

THE AREAS OF INTERVENTION

Within the frame of the studies, at phase 1, a thorough analysis of the current situation in the various areas of the prefabrication workshop was carried out. The situation is outlined in a scheme (see Figure 1), that shows the until-then typical division of the workshop in a cutting-bending area and an area where welding operations are performed. Each area contains its own buffers for intermediate storage of semi-manufactured elements and a stockyard/selection area is the connection between the two shops. The development of these studies led to a modification of this general configuration into an integrated one as shown in Figure 2. This scheme also identifies the critical areas that have been targeted from studies of specific technological work packages (i.e. specific, targeted application fields and related studies). The research project was then broken down to address the critical areas accordingly:

- The profile line,
- The subassemblies area,
- The panel line,
- The flat blocks line,
- The plate bending area, and
- The curved blocks line.

Other work packages that, together with those mentioned above, cover the other issues of the project as listed below.

- The "Measurement Technologies and Quality Control" work package, that has originated most of the studies, concerns the application of new technologies, with particular emphasis to:
  - measurement techniques with advanced sensors like laser and ultrasonic telemeters;
  - vision and image processing systems;
  - tracking system; and
  - robotics systems for workpieces recognition and selection.
- The "Production Management System" deals with the studies of an innovative model for workshop activities, scheduling and management.
- The "Technical Information System" deals with the integration of the existing Information System with the new production technologies defined by the other work packages.

A study of the type and number of pieces to be processed by each area has been made, taking into account the production mix foreseen for the entire workshop. The production mix considers various ship types. As an example, a general comparison between the number and type of elements to be processed relevant to the construction of about 1.5 cruise ships per year or of about 4.5 container ships per year is shown in Table I.

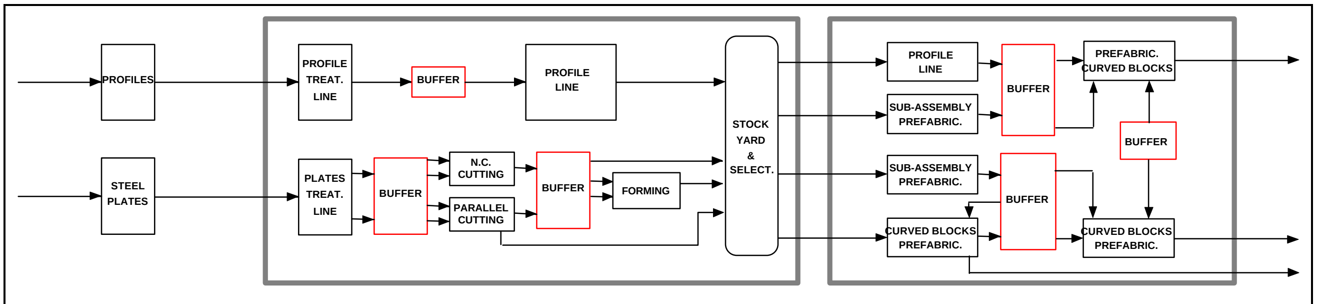

Figure 1- Prefabrication workshop: situation at the starting of the study

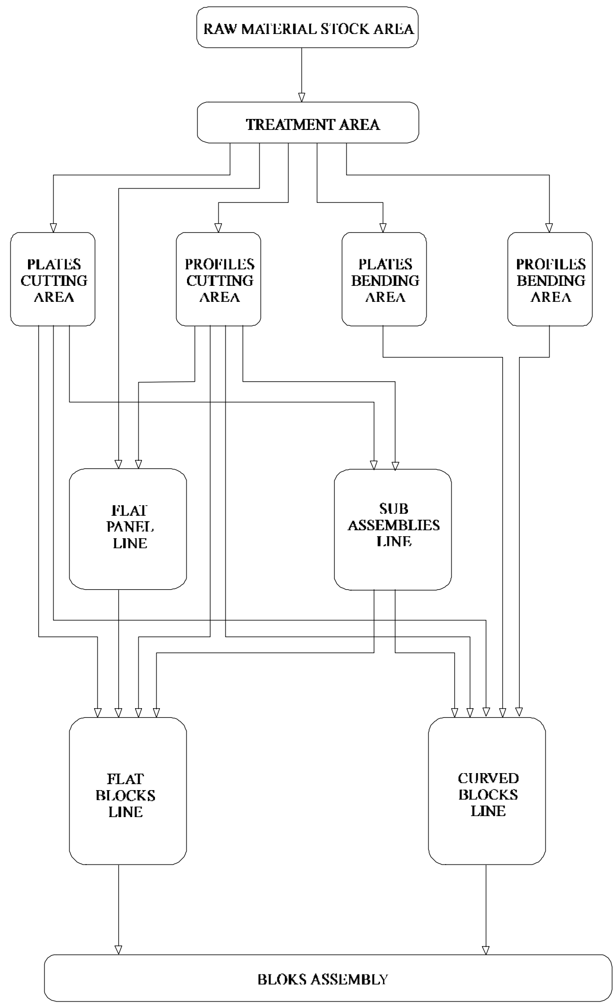

Figure 2 - Prefabrication workshop: new model

For each of the process areas a deep analysis of the current production model has been carried out, taking into account productivity, technologies used, quality of the product, stocking time, minor adjustments, remakes and the resources.

Various new production models have been conceived for each of the areas, taking into account application of the new technologies mentioned and the general targets of the FASP project.

The promising solutions for each area have been tested by production simulation software packages, taking into account the number and type of elements to be processed. That procedure, together with considerations about cost-effectiveness, level of integration between areas, quality requirements for the products and others, have all contributed to outline the final configuration of each area.

THE NEW LAYOUT

As a result of these studies, a new layout for Monfalcone shipyard was developed.
A general description follows.

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A general description follows.

<u>The Profile Line.</u>

It is foreseen to process about 35,000 raw bars per year, with a production of 110,000 - 120,000 finished pieces per year in the new profile line.

The line is provided with a loading buffer, a feeding roller conveyor, a marking/tracing machine and a cutting robot.

WORPIECES PRODUCED PER YEAR SUBDIVIDED ACCORDING TO SHIP TYPE

WORKING AREA	WORKPIECE TYPE	QUANTITY PER YEAR AND SHIP TYPE	
		CRUISE n.1,5	CONTAINER n. 4,5
Treatment line	Plates	9170	12980
	Sections bars	30400	24020
Plates cutting area	Cut pieces	149800	132860
Sections cutting line	Cut pieces	107510	105350
Plates bending area	Curved plates	1830	3450
Sub-assem_ blies area	S.S.A	3570	10400
	S.A.	10800	13710
Flat panel line	Flat panels	870	1030
Flat blocks area	Sub-blocks	500	1200
	"Open" blocks	450	220
	"Closed"blocks	60	320
Curved blocks area	Sub-blocks	150	300
	"Open" blocks	70	110
	"Closed"blocks	20	110
	Special blocks	40	210

Table I

Considering that in the traditional profile processing areas the costs for marshalling cut pieces is higher than the one for the cutting itself, particular attention has been paid to the "logistic" issue. An innovative system, able to automatically palletize the finished pieces, has been designed. Two different and separate pallets' areas have been conceived, with:

- pallets to service the panel line (pieces of about 16 m length); and
- pallets to service the subassembly area (pieces of 0.5 to 5.5 m length).

Sorting is carried out according to specific principles which refer to the Production Management System, where pieces laying on pallets or racks are laid down in the same sequence as clamping in the downstream working areas. This requires maintaining strict tracking and continuous control on pieces at the inlet and outlet of the sorting area. Figure 3 shows the general arrangement of the profile processing area.

The Subassembly Area.

The subassemby area is designed to process 180,000 elementary pieces per year, with an output of about 20,000 subassemblies per year. It consists essentially of a series of dedicated production stations and a transfer system for repositioning pieces being processed from one station to another.
The production stations are of three types: assembly and tack welding, welding, finishing.

The assembly stations consist of robotized systems which, in a

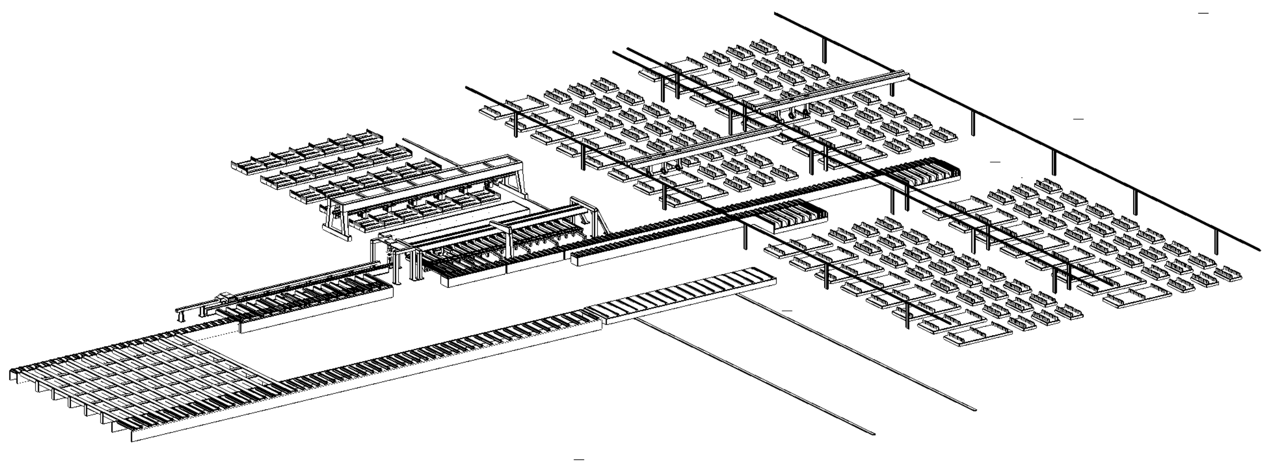

Figure 3 - The Profile Line

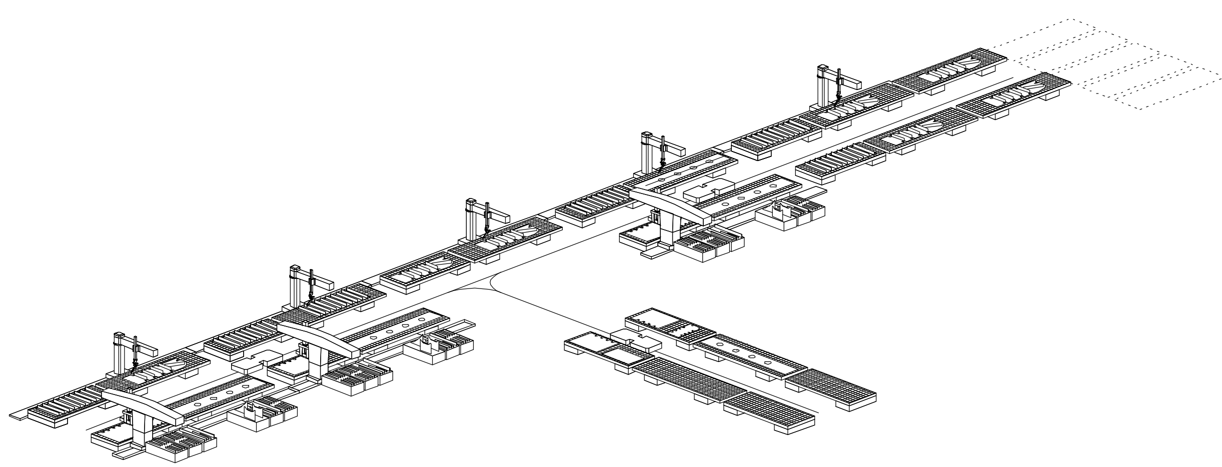

Figure 4 - The Subassembly Area

completely automated way, are able

- to pick up the stiffeners from a pallet/rack (one of those prepared in the profile process area),
- to position them on the plate bases that constitute the subassemblies,
- to push them with the necessary pressure in order to obtain good contact, and
- to perform the spot welding.

The plant is equipped with a vision system in order to identify the precise position and fit of the stiffeners on the bases.

The welding station consists of advanced robotized plants for fully automated finish welding of the subassemblies which are already assembled.

The finishing stations consist of plants equipped for controls and several finishing operations, mainly of manual mode, to be carried out in some of the corners and other minor areas not accessible by the robots.

The various subassembly bases to be processed are arranged over mobile platforms and moved, from one station to the following, by means of a shuttle, baseed on an air cushion system. The shuttle is capable, in a completely automatic way, of taking a platform, transferring and placing it in the proper work station.

The introduction of an automated shuttle, up to now considered to be an innovative solution applicable only in mechanical systems, resulted in a significant improvement in a completely automated carpentry production plant.

A general view of the subassemblies area is shown by Figure 4.

The Panel Line.

The panel line is designed to process about 1,100 panels per year (weight from 5 to 80 tons - thickness from 5 to 40 mm). The panel line consists of the following major components:

- milling machine for plate edge preparation,

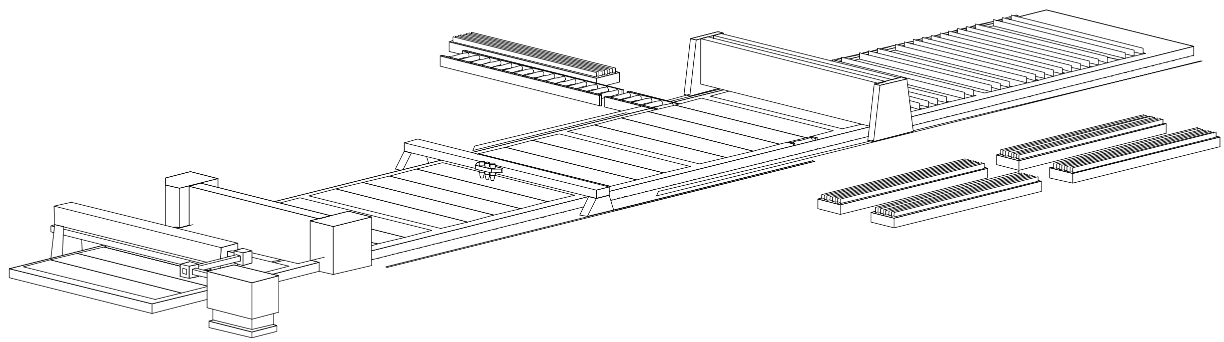

Figure 5 - The Panel Line

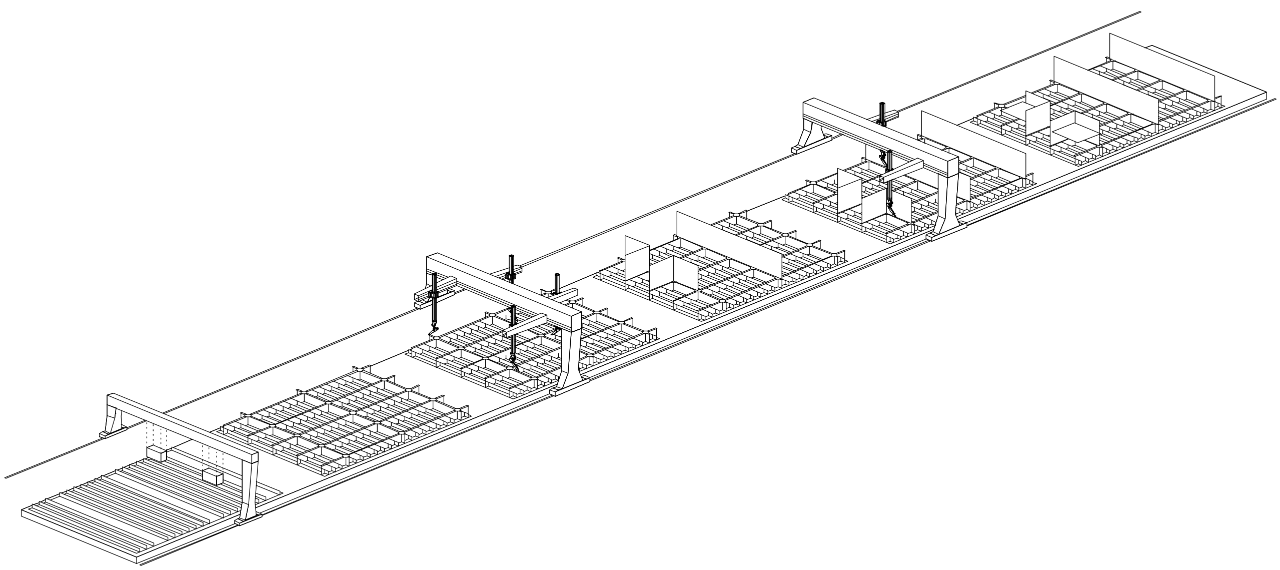

Figure 6 - The Flat Blocks Line

- one-side butt-welding station,
- trimming station for trimming panel edges, and
- stiffeners mounting and welding station.

The one-side butt-welding station is based on the submerged arc welding process, but studies are in progress - following a feasibility study carried out within the FASP program - for a future installation of a laser plant prototype for 16 m long panel butt-welding. The prototype will be completed in the first months of 1997. Compared with traditional submerged arc welding, laser technology offers a measurable advantage in terms of higher welding speed and very limited plate distortion, due to low heat application.

The studies for this new technology application are supported by practical experimentation on 3.5 m long joint welding and are relevant to:

- metallurgic requirements for the steel to be welded;
- definition of the parameters and tests for the welding acceptance by the Classification Societies;
- edge preparation accuracy, in conjunction with the welding plant controller system requirements and the filler wire to be used; and
- particular requirements relevant especially to a relatively long high-power laser beam transmission (due to a 16 m long joint).

A general arrangement of the panel line is shown in Figure 5.

The Flat Blocks Line.

The number of flat blocks to be produced is about 1000 per year. The flat block area includes two quite distinct lines, one for the open flat blocks (i.e. missing one or more sides), the other for the closed flat blocks.

The open block line includes three working areas : assembly, welding and finishing. The assembly areas are equipped with mechanical systems, able to facilitate rational, safe, and ergonomically optimized work, without physical strains on the part of the operators. The area is optimized for production of quality elements, with suitable dimensional tolerances and deformations.

The welding areas are operated by integrated robotized plants. Two gantries, one equipped with four and the other with two welding robots, are arranged for the welding of all the parts of the open blocks.

The closed flat block line is also equipped with three working areas, with a lower level of automation. The transfer of the blocks down the line is by air cushion.

A view of the flat block line is shown by Figure 6.

The Plate Bending Area.

The methods currently used worldwide for both bending the plates and checking the relevant shape, are manual and based on the availability of highly skilled and experienced operators working on non-automated large machines. The human element traditionally plays substantial role in the process.

The steel plates to be processed in the new system are about 2,000 per year, with thickness from 5 to 30 mm.

The technology innovation efforts with FASP have been particularly intensive with respect to this working area. They have focused on the development of a thoroughly innovative approach, based on the exploitation of a computer controlled machine, in order to:

- curve plates with a high degree of precision,
- obtain a drastic reduction of work,
- eliminate remaking at the curved block assembly stage, and
- manage the line in full integration with the other lines and the Information System.

Various possibilities have been investigated for the technology to be applied for plate bending, and for the curvature vision and checking system. The choice made depended on :

- engineering a machine capable of processing plates as large as 16 m x 4 m and
- developing a software capable of receiving information on the actual curvature, comparing it with the final expected values (received from the CAD system) and, according to the relevant comparison results, sending the order to the machine hardware for a next "bending pass".

The line heating methodology is the system chosen for the plate bending machine. Figure 7 shows the configuration of the innovative prototype plant.

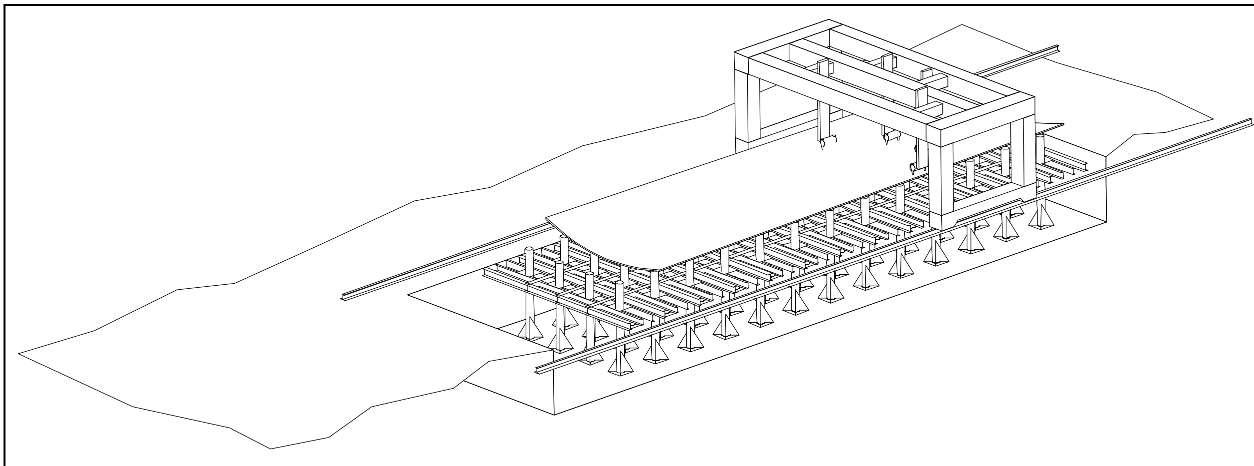

Figure 7 - The Plate Bending Machine

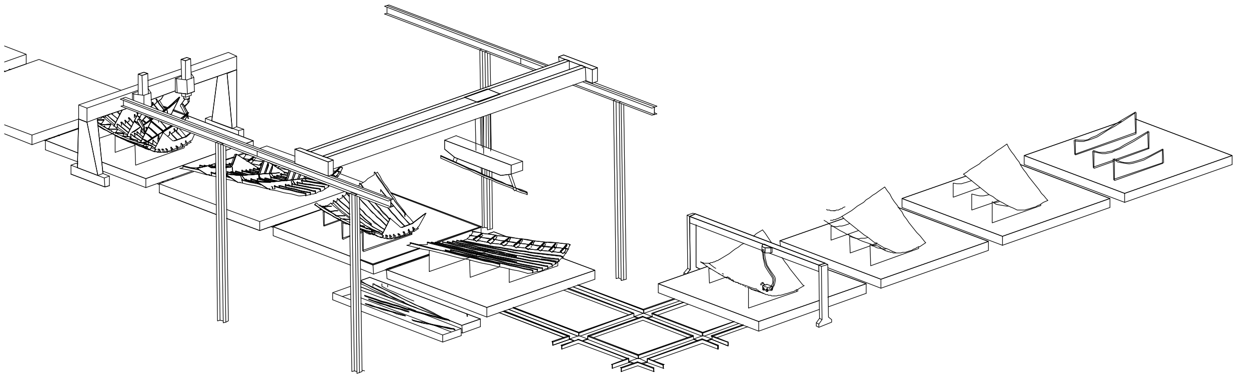

Figure 8 - The Curved Blocks Line

The Curved Blocks Line

The FASP research has identified the families of curved blocks and their quantity, related to different ship types, the planning and the technological problems inherent to the various processes.

The inputs to the line are curved plates, curved profiles and subassemblies, processed in the relevant working areas. In one year about 350 curved blocks are manufactured.

The results of the study are represented both by a considerable reduction of manning and crossing time, and by a high degree of dimensional accuracy.

The curved block line consists of the following major components:

- a number of platforms, moved by an air cushion system;
- robotized arms, arranged on small trolleys, able to butt weld the curved plates in order to obtain the curved panel;
- a manipulator for stiffener mounting and tack-welding, and
- welding stations for stiffeners, with a gantry equipped by two welding robots.

As was the case with the welding robots for the flat blocks, a remarkable effort has been devoted to cut to a minimum, throgh computer simulation, the time necessary for the preparation of the part programs. This issue is discussed in the following pages.

A general configuration of the curved block line is shown in Figure 8.

THE NEW INFORMATION SYSTEM.

The introduction of large numbers of robots and NC machines in the new prefabrication workshop requires numerous modifications in the construction of hull blocks. Such modifications re-echo directly on new requirements for Fincantieri information system, in fact it is necessary:

- generate control and process structured data for a remarkable number of different machines;
- describe the productive operations with greater detail, both for production planning and controlling needs and for correct use of the machines; and
- manage a greater volume of data, in a consistent and controlled way (integration among the various departments, information exchange, variation notification, etc.).

The definition of an implemented information system, able to coordinate and control the shop activities; and to generate, store and manage the necessary new data, was a goal of FASP project.

As mentioned before, the whole of this system is subdivided into two work packages of the project:

- Prefabrication Control System - that covers planning and production controlling topics, and
- Technical Information System - that covers technical data definition and part program generation.

The Prefabrication Control System.

The prefabrication control system deals with two data-management levels, the shipyard information system (level 4) and the workshop information system (level 3). This scale architecture allows the information flows to be clearly defined and facilitates the identification of specific responsibilities.

The shipyard information system provides all the structures required to level 3 to control production activities, such as:

- general planning of all production orders at the shipyard;
- management of materials available from the warehouse; and co-ordination with the technical system, which provides technical documentation for production.

The workshop information system, which receives data from level 4, must synchronize the production activities allocated to individual areas, optimizing the production resources.

Hereinafter the content of the main software components, called subsystems, are described. A data flow diagram (see figure 9) and a brief report of functions supported is given.

Resource Work-Load Check (level 4) - PPR.

The PPR subsystem provides a support for the general planning activity of the shipyard. The processing performed provides:

- scheduling support during milestone verification with a check

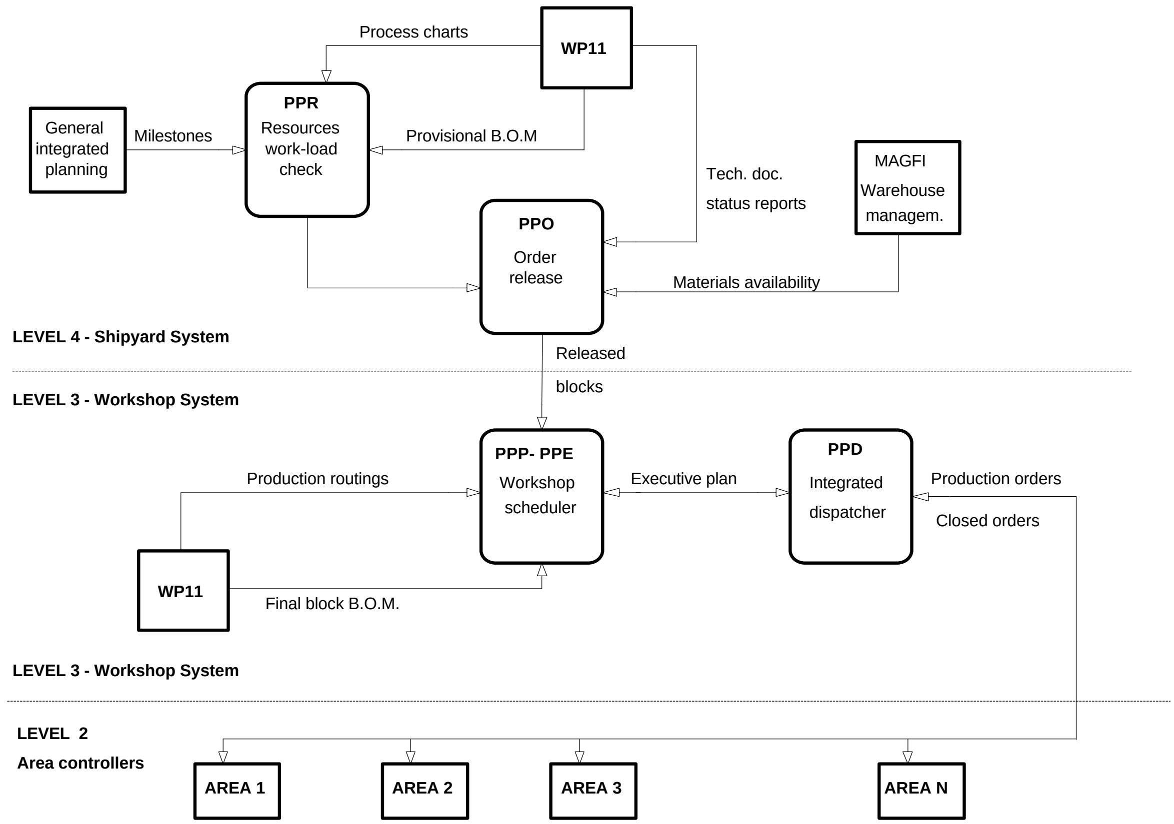

Figure 9 - The Prefabrication Control System. New pattern

on effective capacities of the workshop; and

- a profile of load varying with time, for each resource used in the areas.

Order Release (level 4) - PPO.

The PPO subsystem provides the shipyard production control department with the tools necessary to keep the workshop supplied with feasible production orders. The processing performed provides:

- verification of the feasibility of the orders in terms of primary resources,
- assignment of the materials stored in the warehouse, and
- gathering of all data before sending to the workshop system.

Operative Planning (level 3) - PPP.

The PPP subsystem generates a weekly workshop plan for the orders released by level 4. This planning takes account of the information sent by level 4, of operations introduced or generated locally, and of actual progress of activities already released to areas. The program is also capable of tracking availability of production resources and using the production resource requests specified by production routings.

Executive Planning (level 3) - PPE.

The PPE subsystem performs detailed scheduling daily. The output is the short-term executive plan, which is then taken over by the real-time function of release to the areas.

Integrated Dispatcher - PPD.

The PPD subsystem consists of a set of modules that generate and transmit production tasks to the various areas and receive production progress and other information needed to update the status of the workshop. The system also support the management of communications with areas (level 2), executing driving and monitoring functions.

The Technical Information System.

The main goals of the technical system are the following:

- describing the form and the structure of the hull and getting its

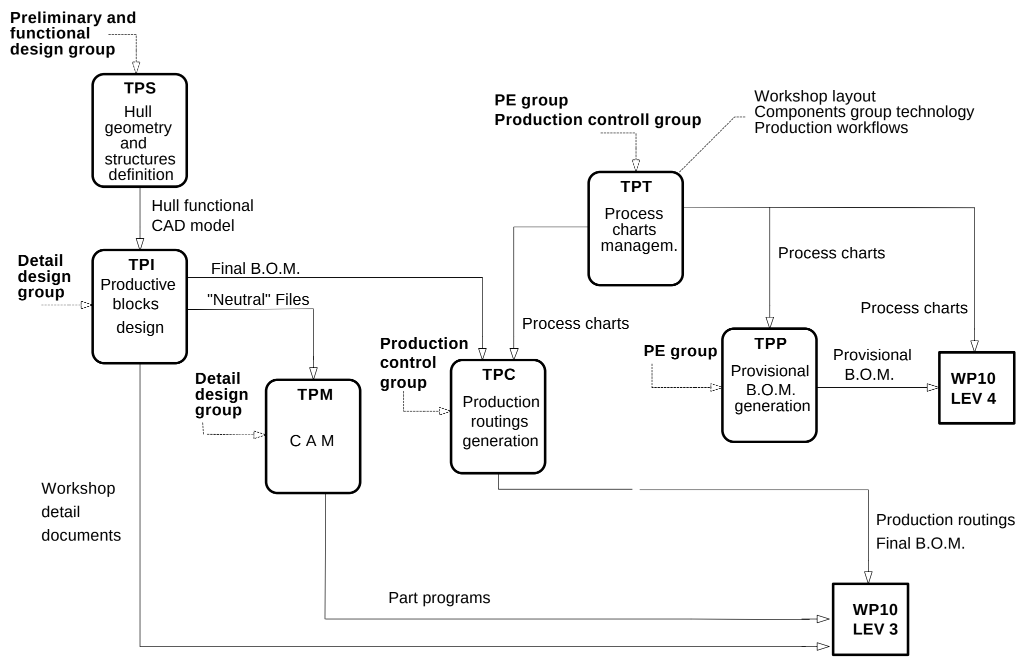

Figure 10 - The Technical Information System. New pattern

drawings;

- storing and managing the technical data needed for detailing the hull construction operations and for getting the part programs necessary for automatic machines;
- supporting group technology concepts to allow the partial reuse of data from previous projects;
- formalizing workshop layout in terms of material flow and resources, and typical workshop products in terms of standard cycle times;
- guiding the complete definition of the product structure (engineering bill of material); and
- managing technical documentation like constructive drawings, technological process, production routings, and part-programs for each component.

A brief report of the main software components functions supported follow (see figure 10 for the data technical system data flow diagram); within the TPM subsystem a particular module is presented as a key example.

Hull Geometry and Structures Definition - TPS.

This subsystem, that is the first one to be utilized in the design cycle, supports the hull basic design and allows the definition and the verification of the geometric model of the main surfaces, and structures.

Productive Blocks Design - TPI.

The TPI subsystem supports the activities connected to block engineering concerning:

- the transformation of the hull functional model into the productive model or block model,
- the creation of the engineering bill of material, and
- the preparation of the detailed technical documentation.

Production Routing Generation - TPC.

The TPC subsystem supports the activities connected to the generation of production routings. These are data structures introduced by the FASP project as representations of the action sequences necessary to produce the various components located by the bill of materials. The routings include data regarding labor and machines to utilize, times necessary to the activities execution, tools, workshop surfaces, equipment and technical documentation.

Provisional Bill of Materials Generation - TPP.

The TPP subsystem create and manage a provisional version of the engineering bill of materials to be used for rough cut planning in the early phase of a ship life cycle, when the engineering is not yet completed and the final bill of materials is not available.

Process Charts Management - TPT.

The TPT subsystem provides the definition and maintenance activities for the logistic model of the prefabrication workshop. The logistic model is a set of data structures representing the productive and logistic flow of the families of components (materials categories) which the workshop can treat, i.e. made inside or purchased outside. The data structures are subdivided into two groups:

- workshop layout, and
- flow of families of components (process charts).

Computer Aided Manufacturing (part program generation) - TPM.

The TPM subsystem implements and verifies the part programs for operation of the numeric control machines and robots. TPM mainly supports work preparation for the following automated production lines and areas:

- Robotized profile sections cutting and palletizing,
- NC sub-assemblies mounting and robotized welding,
- NC panel line,
- Robotized flat blocks structures welding, and
- Robotized curved block structures welding.

An Example: TPM.B - Arc-Welding Robot Off-Lline Programming System.

Historically, ships have been manufactured as one of a kind products with great variation in design, construction and build. Traditional welding methods typically required about 70 hours of programming per 1 hour of robot welding. Programming was done on-line. This means that the robot was taken out of production the entire time needed to create programs.

In shipbuilding, nearly every single ship is a prototype: two ships can be very similar but not identical. This means that every single ship component (i.e. ship section, ship block, ...) requires programs that are unique.

By using off-line programming, shipyards can reduce the programming time to only a fraction in comparison with traditional on-line programming.

Fincantieri chose simulation software to achieve curved and flat block off-line programming. Simulation products offer built-in libraries of most common industrial robots (geometry and kinematics model), standard torches, positioners, gantries, and related equipment. Workcells are easily developed using these built-in libraries. Nonstandard components of the workcell, like the workpiece (in our case curved blocks), are imported via IGES from the CAD model.

Starting from a standard commercial product, a layer of software has been developed to allow a rapid and efficient programming of robots.

The development that has been performed is based on the following concept.

The majority of welds used for ship construction can be categorized into families. Each family can be programmed as a "primitive" or template, then parametrically mapped to each weld seam. In this way, programming curved blocks - with highly individual and curved seams - for example, is as easy as programming flat blocks having mainly flat and similar sections.

The primitive capture years of welding experience and form a

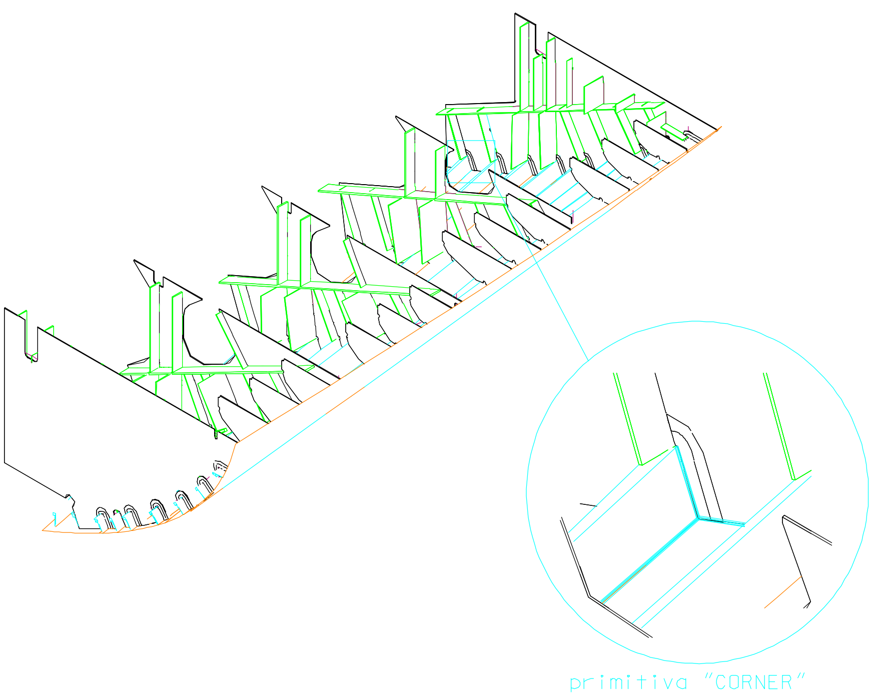

Figure 11

knowledge base for preserving vital information.

Thus an off-line robot program can be created in nearly the same amount of time as the robot work cycle itself.

Primitive.

User defined parameter values are used to define tag locations, orientations and auxiliary data. This allows one to dramatically limit the number of interactions by the user. Rapid selection of weld zones that have similar, but not identical, geometry as is commonly found in ship structures (see figure 11).

A parameter popup is used to define the location and orientation, with respect to part geometry, of individual tag points. It is also used to define starting and ending conditions (i.e. distance, surface, vertex, etc.).

This popup is generated by what are referred to as primitive files. Primitive files consist of system variables and keywords that define how and where to generate weld paths.

Primitive files contain variables used to define the location and orientation of tag points (tag points are used for indicating destination positions for robot motion) in and around a joint or combination of joints.

Libraries of primitive files have been created to define standard, or unique, joint configurations. Keywords are available that can actually restrict the simulation system operator from modifying primitive system variable values. This helps ensure that important system variable values, that are defined by a weld engineer, cannot be modified during primitive execution.

A primitive file can be invoked using standard buttons of the simulation environment.

Once invoked, user-defined prompts contained in the primitive file can be used to indicate the type of geometry selections required to define the weld joint(s).

Primitive and Weld Process Data

A set of functions and variables are available to define robot specific weld process parameters including those parameters that allow the control of sensors like camera and arc seam sensing.

It is also possible to reference external weld process data files. This process data file must exist in the process library and must be loaded into the robot welding device. Table references will be automatically placed in the appropriate tag points. When the appropriate function is invoked, a robot program is automatically generated with the appropriate weld data references.

Primitive and Off-Line Programmers

The majority of robot programming is done by users that are not computer or robot experts. Therefore, it is essential that the system is easy to use and smart enough to maintain important weld procedural information defined by weld engineers.

This is why primitive libraries are created before the programming is done. In this way robot and weld engineers can identify typical weld zones and structures and study appropriate primitives. One of these primitives is able to place weld paths with more than 50 points in just few mouse clicks.

The end user of the off-line system does not have to take care of these single points. The end user have to consider just the seam, and decide which seam configuration is better for a given geometry. Via points to ensure collision-free motion between weld joints are automatically generated. To minimize robot cycle times, weld paths are logically ordered and sequenced. Complex camera sensors and robot master slave configurations are also inserted by the primitive without any input required from the end user.

Primitive and Interactions

Using the primitive system the number of user interactions is dramatically reduced. To program a certain typical area of a block, the user only needs to execute the correct primitive and select the weld zone with few mouse click on the “most meaningful” surfaces.

Reduction of the user interactions means that the system is automatically executing most of the operations and therefore errors due to wrong user inputs decrease.

For this reason primitive make robot programs generated off-line more reliable.

Primitive and Methods

In addition to automatic path generation, a mechanism able to detect errors and correct them is available to the weld and robot engineer that is developing primitives.

During primitive execution, "methods" detect collisions, near misses and joint limits. Specific “rules” inserted into the primitive file tell the system how to behave and how to modify tag points in order to correct the error situation.

In this way test and modification become activities that are executed automatically by the system. Users do not have to take care of these tests and modification any more.

Methods help making off-line programming system more rapid and efficient.

Robot programs became less sensitive to the user skill for what concern quality.

CONCLUSIONS

The first application to actual production of the new system herein described was for the construction of a 77,000 gross tons cruise ship with a passenger capacity of 2,400 in 1,050 cabins. The results of this application have confirmed the effectiveness of the solutions adopted and the real possibility to meet the targets as originally foreseen.

The particularly high percentage (more than 50%) of labor for passenger ships outfitting in respect to the workforce devoted to the hull, suggests undertaking a project similar to the one described above covering the various outfitting activities. This field is considered at the moment to be among the most rewarding issues for the research in the near future.

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Producibility Cost Reductions Through Alternative Materials And Processes

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ABSTRACT

The competitive nature of shipbuilding requires that successful builders use the most cost effective means to construct their ships. This paper describes ongoing research to test the use of alternative materials and processes to reduce material and labor costs. Some of the traditional methods and materials used in shipbuilding are questioned and alternatives are evaluated. The research, backed by the NSRP through the SP-8, Industrial Engineering Panel of the SNAME Ship Production Committee, looks specifically at fiberglass and plastic pipe, adhesives and rubber hose as areas where cost and producibility gains may be found. Cost comparisons between traditional and alternative methods will be presented as well as applicability to regulatory and classification society requirements.

NOMENCLATURE

ASTM	American Society for Testing and Materials
FRP	Fiber Reinforced Plastic
GRP	Glass Reinforced Plastic
NSRP	National Shipbuilding Research Program
PVC	Poly Vinyl Chloride
SNAME	Society of Naval Architects and Marine Engineers
SP	Ship Production Committee Panel

INTRODUCTION

The competitive nature of shipbuilding requires that successful builders use the most cost effective means to construct their ships. The SP-8, Industrial Engineering Panel of the Society of Naval Architects and Marine Engineers (SNAME) Ship Production Committee, frequently studies the mechanics of the ship production process and looks at ways to make the process more efficient and cost effective.

The SP-8 Panel developed the project as part of the National Shipbuilding Research Program's (NSRP) FY95 program to look specifically at fiberglass and plastic pipe, adhesives and rubber hose as alternatives to traditional materials and processes. This paper describes ongoing research conducted by the Marine Systems Division of the University of Michigan Transportation Institute, the Shipyards Division of Avondale Industries and Damilic Corporation, to investigate and test the use of alternative materials and processes to reduce the overall costs (including life cycle) of ships. For each of the subject focus areas of fiberglass and plastic pipe, adhesives and rubber hose, traditional methods and materials are questioned and alternatives are evaluated. The research task arrangement is as follows.

- Task 1. Identify Areas of Potential Use
- Task 2. Identify Function Specifications
- Task 3. Identify Potential Candidates
- Task 4. Test and Evaluate Candidates
- Task 5. Seek Regulatory Acceptance

The research team has established the most likely areas where adhesives, flexible hose and fiberglass pipe can be used to save significant time and cost. A preliminary list of items in each of the interest areas was developed and has been expanded through shipyard visits and discussions about the work of the project team and the SP-8 Panel. The first three tasks are nearly completed and on site testing is to follow shortly. Regulatory considerations are being checked in parallel.

The focus of the research is primarily on applications to commercial vessels, followed by naval auxiliaries and combatants. This research is in progress will be released as an NSRP report in the summer of 1997.

AREAS OF POTENTIAL USE

Adhesives

The adhesives area seems to be the most promising in the area of labor savings. The research is centering on the choice of adhesives that offer the best combination of holding power and ease of application without some of the negative attributes of volatile compounds (that would require additional ventilation, worker protection, or both) or excess preparation.

Adhesives bonding is an alternate means for mechanical fastening and welding non-structural and non-critical shipboard items. Adhesives also provide a means for easy on site repair or modification to fixtures. Potential shipboard applications for adhesives include clocks, thermostats, attachment of small diameter pipe and gauge tubing, label plates, brackets, and curtain plates (see Table I). These attachments can be exposed to temperatures between -18^{o}C and 49^{o}C (0 ^{o}F and 120^{o}F) and a relative humidity of 90% or more, during both installation and service life. Adhesives can be formulated to be either thermally conducting, electrically insulating or visa versa.

Bonded Items	Bond Area (sq. in.)	Comments
Curtain Plates	100-2000	Vertical placement, large surface area, good tack or green strength desired
Equipment Brackets	10-200	Vertical placement, high strength needed, long working time desired
Equipment Foundations	100-2000	Large volume application, strength and durability required
Insulation Mounting Clips	10-50	Long working time not necessary, good tack, medium strength, good temperature resistance
Label Plates	10-200	Long working time not necessary, low strength, good peel strength
Pipe Hangers	10-50	Intermediate fixturing time desirable, medium to high strength
Plumbing Fixtures	10-200	Low to medium strength, hydrophobic, attachment to plastics and other materials
Thermal/Acoustical Insulation	50-1500	Good tack, medium strength, good temperature resistance
Wire Hangers	10-50	Various levels of strength required, attachment over various substrates, easy attachment late in the building process
Zinc Anodes	50-250	Medium strength, electrically conductive, eliminates the need to weld stainless steel studs, eliminate chasing threads on studs for replacements

Table I - Candidates for Attachment by Adhesives.

Many forms of structural adhesives are available commercially. Table II describes the five most widely used chemically reactive structural adhesives (1):

- Epoxies,
- Urethanes,
- Acrylics,
- Cyanoacrylates, and
- Anaerobics.

Candidate adhesives were selected from a broad review of commercially available adhesives because of their general utility (Table III, page 4) and because they:

- Can be cured at ambient temperatures with minimal additional heat required,
- Pose minimal exposure hazard to workers, and
- Can be easily applied with a trowel, caulking gun, syringe, or gun dispenser.

Chemical Family	Advantages	Comments
Epoxy	High strength, good solvent resistance; good elevated temperature resistance; good gap filling capa-bilities; wide range of formulations	Ambient cure is almost always a two component system which requires either metering and premixing or dispensing equipment. Short pot life.
Polyurethane	Flexible, tough; is used in adhesive sealant formulations	Moisture sensitive; if purchased as a two component system one component is unreacted isocyanate - a toxic chemical
Acrylics	Good flexibility; peel and shear strength, will bond oily surfaces room temperature cure, moderate cost	Some are toxic and flammable (modified acrylics); more expensive than general purpose epoxies
Cyanoacrylates	One component, good adhesion to metal, minimal quantities required	Instant cure limits fixturing time, low viscosity, good capillary action, more commonly known as super glue
Anaerobic	One component, long pot life, nontoxic	Thread locking adhesive, brand names include Locktite®

Table II Adhesives Types.

Adhesives Testing

From the list in Table III, seven epoxies and four acrylic based adhesives (Table IV) were tested for their performance, ease of use, and compatibility with primed steel and a smooth aluminum surface. Cyanoacrylates were not pursued because they are susceptible to hydrolytic attack.

Epoxies	Acrylics
Lord 320	Hernon 761,730
TA-30	Lord 206/19
Epoxies, etc 10-3005	AA 4325
Norcast FR 7316	Plexus MA310
Magnolia plastics	
Lord 310	
Armstrong A-12	

Table IV. Tested Adhesives.

The preliminary screening of the selected adhesives was as follows. Primed steel plates 300mm x 300mm x 3mm (12 in. x 12 in. x 0.125 in.) weighing roughly 2.3 kg (5 lbs.), representative of a ship's joiner bulkhead, were cleaned with acetone and scoured an abrasive pad (to remove loose debris). The acetone removes most of any finish paint but only a minimal amount of primer. A generous amount of adhesive was applied to a small area on the steel plate (oriented horizontally) either through a syringe mixing applicator or with a putty knife (after mixing the two components by hand). The plate was then turned to stand vertically. A formed 0.1mm (0.003 in.) aluminum foil cup was placed right side up on top of the adhesive. Hand pressure was applied to distribute the adhesive evenly between the substrate pair (aluminum / steel). All of the adhesives except three (relatively low viscosity) exhibited sufficient tack to support the aluminum on a vertical surface immediately after application. Following an overnight cure at room temperature, adhesive strength was tested by lifting up the steel by the rim of the foil cups. Of the eleven adhesives tested, five (Table V) bonded well enough to lift the whole steel plate. This was as much a tensile as a peel test.

Adhesive	Average Lap Shear Strength (psi)	Standard Deviation
AA4325	658	282
Lord 206/19	2631	484
TA-30 Philibond	2560	605
Norcast 2316	3270	142
Lord 320/322	2570	276

Table V. Adhesives Passing the Preliminary Test and Tested for Lap Shear.

Adhesive Type	Brand Name	Material Form	Applicable Substrate	Application Method	Cure Conditions	Special Features
epoxy	DAPCO 3004	two component	metal, wood, concrete, plastic	extrusion, trowel	4 hours	3,000 psi tensile strength
epoxy	Magnobond 6155	two component	plastic	trowel	7 days @ 70^{o}F	same as above
epoxy	Norcast 7285-1	one component	metals, plastics,	trowel	3 hrs @ 250^{o}F	fire retardant
epoxy	Norcast 9310	two component	general purpose	casting resin		
epoxy	Lord 310, 320	two component	steel, wood, FRP	syringe	24 hrs @ 77^{o}F	resists moisture, sunlight, thermal cycling, 320 is toughened for impact
epoxy	Epoxies, etc 10-3050	one component	steel	trowel	24 hrs @ 77^{o}F	8,000 psi tensile strength
modified acrylate	Advanced Adhesives Systems 4325	two component	primed steel/fiberglass	dispensing gun	24 hrs @ 77^{o}F	3,500 psi ten strength/ high humidity
acrylate	Dymax 828	liquid, two part	primed steel	brush or bead on	local pressure	3,000 psi ten strength/ 300^{o}F
epoxy	Armstrong A-12	liquid, two part	primed steel	brush or bead on	local pressure	Milspec epoxy, 2900 psi 300^{o}F
methacrylate	Plexus MA-310	liquid, two part	steel/fiberglass		local pressure	250^{o}F/tough
epoxy	Masterbond EP76M	liquid, two part	steel/fiberglass	trowel	24 hour @ 77^{o}F	300^{o}F
epoxy	Philadelphia Resins TA-30	two component	metal, rubber, wood, glass	trowel	24 hours @ 77^{o}F	very high tack
cyanoacrylate	Pacer Tech. M-100	100 cP liquid	primed steel	rough, clean	instant 30 sec	poor with moisture, brittle
cyanoacrylate	Pacer Tech. HP-500	5000 cP paste	general	brush on	1 min	
cyanoacrylate	R-X	thick	general	gel, paste	2 min	
epoxy	West Systems 105/205 hardener	two component	fiberglass, steel	hand mixed brush on	8-24 hrs @ 77^{o}F	no post cure, 200^{o}F no load 130^{o}F w/load
Polyester	ATC Chemical - Poly-bond B41F	two component	fiberglass, steel	thix. paste, putty knife, trowel	24 hrs @ 77^{o}F	tough, low shrinkage, used in FRP hull to deck marine applications
urethane	Sika 241	one component	steel, fiberglass,	gun dispenser	24 hrs @ 77^{o}F	semi permanent
urethane	3M Scotch-Seal 5200	one component	steel, fiberglass,	dispenser, trowel	24 hrs @ 77^{o}F	semi permanent
acrylic/Ag/Ni	3M 9703	tape	alcohol wipe, abrasion	40 psi pressure	72 hrs	conductive, 250^{o}F
methylmeth-acrylate mod	Hernon MI React 730; Act 56 and React 761; Act 63	two component	unprimed steel primed, painted	syringe appl bead on trowel (761)	24 hrs @ 77^{o}F	visc 6000 cps, 1-2 min fix time tensile str 3.000 psi/grit blast steel; -60^{o}F -250^{o}F; nonflammable
acrylic	Lord 206	two component	unprimed steel primed, painted	syringe type caulking gun	24 hour @ 77^{o}F	minimum prep, excellent moisture, temperature and UV resistance.
cyanoacrylate	Quantum 108	one component	steel	oily surfaces ok; wicking action	instant 5-20 sec	not good around water and moisture

Table III. Preliminary Adhesives Selection Table

Following this test the adhesive assembly was placed in an hot and humid test chamber (an oven heated to 100°C (212°F) containing a pan of boiling water). Using protective gloves, the strength bearing capacity of the bonded aluminum and steel assembly was tested again. Four of the five adhesives: TA-30, Norcast FR2316, Lord 206/#19, and Lord 320/322 experienced no noticeable loss of strength. A slight loss of strength, exhibited as peeling was observed for the AA 4325 adhesive.

For these five adhesives, laboratory lap shear specimens were prepared from 100 mm x 25 mm (4 in. x 1 in.) coupons machined from primed steel plate and tested according to ASTM D1002. In order to be accommodated by the grips in the tension testing machine, one end of each coupon was machined to a 1.6mm (.06 in.) thickness. As before, surface preparation was limited to a solvent wipe with acetone and a mild scouring with an abrasive pad. Five lap shear specimens were prepared and tested for each of the five adhesives. The lap shear test results are provided in Table V.

In addition to their ability to bond to smooth and rough metal surfaces, a high initial tack makes these adhesives ideally suited to bonding applications on a vertical surface such as a bulkhead.

Based on the above results, the four highest strength adhesives have been selected for further testing at the shipyard. The two component thixotropic paste epoxies can be applied either manually with a trowel or putty knife, or with pneumatically operated dispensing equipment. The other epoxy adhesives are available in a double barrel syringe type applicator. The acrylic adhesive is also available in higher viscosity so that it can be applied with a caulking gun.

Flexible Hose

The use of flexible hose in commercial and military shipbuilding has been approved by classification societies and regulatory bodies well beyond its current state of new construction general usage. With the advent of new materials, testing has been performed and approvals have been secured for the use of flexible hose in a number of areas. A general lack of awareness of the extent to which the use of flexible hose has been approved, coupled with the natural inclination of shipbuilders to retain the use of traditional shipbuilding practices and materials, has inhibited the widespread use of flexible hose to the extent allowable.

The researech team has not discovered thorough studies that have analyzed the potential labor savings from the use of flexible hose to the extent allowable under current approvals. Table VI depicts the current areas of approval for various flexible hose applications.

In determining the suitability of flexible hose for a given application, hose assemblies are first classified as critical or non-critical depending on the system they are used in and the redundancy in that system. The level of criticality determines the replacement cycles for various hose assemblies and thereby contributes to determining the type of hose approved for use. In determining the level of criticality assigned to a given hose, the following attributes are considered and weighted as pertinent factors.

System. The system category is divided into five major sections, each reflecting a fluid type, except for drains, which are all inclusive.

- Gasses
- Water
- Sea water
- Drains
- Oil systems

Pressure Ratio. The pressure ratio is determined by dividing the rated working pressure of the hose by the system working pressure

Impulse. Impulse is defined as any pressure spike that momentarily raises the pressure in the hose.

Temperature. This is the working temperature range of the hose including the maximum temperature that the hose could be exposed to.

The project team is currently identifying and documenting those areas in which the use of flexible hose is acceptable according to classification societies and regulatory bodies, and comparing the potential use to actual existing standard shipyard practice. The potential labor savings and ancillary economies that could be recognized by fully adopting the use of flexible hose in all approved areas is being analyzed.

It is anticipated that the incorporation of flexible hose to the extent currently allowable in new ship construction would reduce manufacturing, modification, and repair costs as well as reduce vessel weight and reduce long term maintenance, operation and repair costs.

PVC/GRP Pipe

The use of Poly Vinyl Chloride (PVC) or Chlorinated PVC (CPVC), also called plastic pipe, and Glass Reinforced Plastic (GRP) or Fiber Reinforced Plastic (FRP), also called fiberglass, pipe on board commercial as well as military ships has proliferated substantially although sporadically over the past

HOSE TYPE	REINFORCED	WATER							OIL						GAS			APPROVALS
		FRESH	SALT	DEIONIZED	POTABLE	REACTOR EFFLUENT	CONDENSATE	STEAM	OIL BASE	FIRE RESISTANT	WATER BASE	DIESEL	JP-5	LUBE	AIR	NITROGEN	REFRIGERANT	
SYNTHETIC RUBBER	2 WB	X	X			X	X		X		X	X		X				MIL-H-24135
SYNTHETIC RUBBER	TB / 4 SW	X	X				X		X		X	X		X				MIL-H-24135
SYNTHETIC RUBBER	TB / 4SW								X		X							MIL-H-24135
SYNTHETIC RUBBER	2 WB	X	X			X	X		X		X	X		X				MIL-H-24135 SAEJ1942
SYNTHETIC RUBBER	2 WB														X	X		MIL-H-24135 SAEJ1942
SYNTHETIC RUBBER	4 SW								X									MIL-H-24135 SAEJ1942
SYNTHETIC RUBBER	TB / 1WB /TB	X	X				X		X			X		X				MIL-H-24135 SAEJ1942
AQP	TB / 1WB	X	X				X		X			X		X	X	X		MIL-H-24135 SAEJ1942
AQP	2 WB	X	X			X	X		X			X		X				MIL-H-24135 SAEJ1942
SYNTHETIC RUBBER	TS	X	X				X		X			X		X				MIL-H-24136
SYNTHETIC RUBBER	TB	X	X				X		X			X		X				MIL-H-24136
SYNTHETIC RUBBER	TB	X	X				X		X			X		X				MIL-H-24136 J1942
SYNTHETIC RUBBER	TS	X	X				X					X		X				MIL-H-24136
SYNTHETIC RUBBER	TB	X	X						X			X	X	X				MIL-H-13444 TYPE 1
SYNTHETIC RUBBER	TB / 1WB								X			X		X				MIL-H-13444 TYPE III
SYNTHETIC RUBBER	WB	X	X										X	X	X			MIL-H-13531 TYPEI
SYNTHETIC RUBBER	2 WB								X			X	X	X				MIL-H-13531 TYPE II
SYNTHETIC RUBBER	WB																X	S6430-AE-TED-010
PTFE	SSB	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		MIL-H-38360 , AS1339
PTFE	SSB	X	X	X	X	X	X	X				X	X	X	X			SAE J 1942
CONVOLUTED PTFE	SSB	X	X	X	X	X	X	X				X	X	X	X			SAE J 1942
CONVOLUTED PTFE	SSB	X	X	X	X	X	X	X				X	X	X	X			SAE J 1942

WB = WIRE BRAID
TB = TEXTILE BRAID
SSB = STAINLESS STEEL BRAID

TS= TEXTILE SPIRAL
SW = SPIRAL WIRE
* SAE J 1942 = COAST GUARD APPROVAL

Table VI. Flexible Hose Applications and Approvals

several years (2-5). Several recognized classification societies and regulatory bodies have approved the use of fiberglass pipe in designated areas, other areas have not been addressed or do not currently have widespread approval.

The team's preliminary consideration for application of PVC and CPVC pipe is in:

- Potable water,
- Exterior deck drain,
- Low pressure air,
- Fresh water,
- Sea water washdown,
- Chill water,
- Hot water, and
- Sanitary drainage systems.

GRP pipe is likely to gain acceptance in the following systems:

- Seawater fire main,
- Seawater intake cooling,
- AFFF,
- Seawater overboard discharge,
- Oily water transfer,
- Crude oil washing ,
- Ballast tank flood and drain systems, and
- Cargo oil systems within tanks.

A chart of current approvals for GRP piping is listed in Table VII.

	ABS	USCG	LLOYDS	DNV
Inert gas (effluent overboard lines only through machinery or cofferdams)	YES	YES	YES	YES
Inert gas - distribution lines on deck	YES	YES	YES	YES
Sanitary / Sewage	YES	YES	YES	YES
Cargo piping - except on deck, in machinery spaces, and in pump rooms	YES	YES	YES	YES
Ballast system	YES	YES	YES	YES
Crude oil washing - in the tanks (not on deck)	YES	YES	YES	YES
Fire system	NO	NO	NO	NO
Cargo vent piping - within tanks only	YES	YES	YES	YES
Chilled and hot water system	YES	YES	YES	YES
Bilge system	NO	NO	NO	NO
Fresh and seawater cooling systems - aux.	YES	YES	YES	YES
Fresh and seawater cooling - vital	NO	NO	NO	NO
Cool steam condensate return system	YES	YES	YES	YES
Sounding tubes	YES	YES	YES	YES
Fire systems - offshore production platforms	N/A	N/A	N/A	N/A

Table VII. Classification Society and Regulatory Body Approval for GRP Pipe.

With the recent introduction of poly-siloxane modified phenolics in fiberglass pipe fabrication, a number of previously beneficial attributes of fiberglass pipe have been enhanced and a number of significant advances have been attained. At the same time, some heretofore negative characteristics have been mollified. Tables VIII and IX lists some of the positive and negative attributes of conventional phenolics an the newer poly-siloxane modified phenolic pipe materials.

A substantial amount of testing has been performed to verify the enhanced physical characteristics as well as improved fire performance of poly-siloxane modified phenolics. Among these tests are the following:

- IMO fire endurance testing - level 3 - eight tests carried out in two sizes and four configurations - in accordance with ASTM F1173 -95;
- SINTEF jet fire;
- ASTM E-84 - standard test method for surface burning characteristics of building materials;
- Pittsburgh toxicity;

- ASTM E-162 - test method for surface flammability of materials using a radiant heat energy source;

CONVENTIONAL PHENOLICS	
Positive Attributes	**Negative Attributes**
Excellent high temperature resistance	Poor adhesion for bonded joints
Low flame spread	Limited pressure performance due to low elongation and brittle nature
Corrosion resistance	Limited impact resistance
Low smoke and toxicity in fire	
Light weight	

Table VIII. Attributes of Phenolic Pipe

POLY-SILOXANE MODIFIED PHENOLICS	
Positive Attributes	**Negative Attributes**
All the same plus	To be seen.
Improved fire resistance	
Improved adhesion (160 %)	
Improved elongation (30 %)	
Improved impact resistance (40 %)	

Table IX. Attributes of Poly-Siloxane Modified Phenolic Pipe.

- ASTM E-662 - test method for specific optical density of smoke generated by solid materials;
- ASTM D-635 - rate of burning and/or extent of burning of self supporting plastics in a horizontal position;
- ASTM E-1354 - test method for heat and visible smoke release rates for materials and products using an oxygen consumption calorimeter;
- Lap shear strength physical;
- Short term burst;
- Hoop stress;
- Impact resistance;
- Flexural;.
- Modulus of elasticity;
- Chemical resistance;
- Weathering resistance;
- Steam resistance; and
- Corrosion resistance.

Comparison To Metallic Piping Systems. Compared to metallic piping systems, fiberglass, composite or plastic piping has a number of advantages. The following list shows some of the detractors of metallic materials compared to plastic.

- Carbon Steel is inherently corrosion prone and requires constant maintenance and frequent replacement. requires high level of installation and/or repair expertise.
- Copper Nickel has high initial material and installation cost but is costly to repair or modify and requires a high level of installation and repair expertise.
- Stainless Steel also has a high initial material and installation cost and is costly to repair or modify.
- Fiberglass Pipe has a moderate initial installation cost, will not corrode, has very low maintenance and a low skill level is adequate for installation. FRP pipe modification and repairs can be accomplished without certified welders, welding machines or burning equipment.

Table X is a comparison of the installed costs of a typical 100mm (4 in) offshore fire protection piping system.

Pipe System Material	Cost per Meter	Cost per Foot
Carbon Steel	$82	$25
Copper Nickel	$295	$90
Stainless Steel	$312	$95
Composite	$115	$35

Table X. Comparative Cost of a Fire Protection Piping System

The composite fire protection piping system, with intumescent coating, is capable of maintaining serviceability of the pipe for a minimum of three hours in a severe fire test. The life cycle advantages of the non-corroding composite pipe are expected to overcome the installed cost disadvantage.

With this type of performance available, the goal of the project is to promote the certification and approval of fiberglass pipe into areas currently not approved including:

- cargo piping,
- fire system piping,
- bilge systems,
- freshwater cooling,
- sea water cooling, and

- similar critical areas.

The project team is promoting the acceptability of fiberglass pipe for use on military vessels as already approved by non-military regulatory and classification societies.

The expanded incorporation of fiberglass pipe on both military and non-military vessels is expected to reduce manufacturing, modification, and repair costs as well as reduce vessel weights and lower long term maintenance and operation costs.

CONCLUSIONS

Initial findings of the team are that the alternative materials in the study are capable of reducing material and labor costs significantly in certain areas. Although this particular project is related to just adhesives, plastic and fiberglass pipe, and flexible hose, a methodology is being set up to consider the use of alternatives to traditional materials and methods in other areas of shipbuilding.

The use of adhesives to replace welding and mechanical attachments can save both material and labor costs. Adhesive strengths are adequate to support a number of shipboard items currently attached mechanically. The epoxies promise to provide base material protection so that make-up painting is not required.

Ongoing cost benefit analyses will determine the best applications of composite and plastic pipe and flexible hose. Fire protection and critical systems considerations are the focus of the research.

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STEP Implementation For U.S. Shipbuilders - MariSTEP Progress Report

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ABSTRACT

MariSTEP is a DARPA/MARITECH sponsored cooperative agreement among several shipyards, CAD vendors, and a major university to prototype the exchange of shipbuilding data between diverse shipyard environments using STEP, an International Standard for the Exchange of Product Model Data. The goal of the three year MariSTEP effort is to implement transfers using the STEP Shipbuilding Application Protocols to exchange product model data among the participating shipyards. The project is in its first year, and this paper reports on the progress made thus far, along with outlining the overall project plans.

NOMENCLATURE

AP	Application Protocol
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CIM	Computer Integrated Manufacturing
DARPA	Defense Advanced Research Projects Agency
DXF	Data Exchange Format
EMSA	European consortium to develop STEP Standards for Shipbuilding; Active from 1996-1999
ERAM	Engine Room Arrangement Model
IGES	Initial Graphics Exchange Specification
ISO	International Organization for Standardization
MariSTEP	DARPA funded project for Development of STEP Ship Model Database and Translators for Data Exchange Between Shipyards
MARITIME	European consortium to develop STEP Standards for Shipbuilding; Active from 1992-1995
NEUTRABAS	European consortium to develop STEP Standards for Shipbuilding; Active from 1988-1991
NIDDESC	Navy / Industry Digital Data Exchange Standards Committee
PMDB	Product Model Database
SQL	Structured Query Language
STEP	Standard for the Exchange of Product Model Data

INTRODUCTION

The MariSTEP program is a unique implementation effort with the team membership representing a diverse combination of shipyards and CAD vendors. Using STEP (the Standard for the Exchange of Product Model Data), the team aims at the exchange of shipbuilding data among the five differing environments represented within the membership. Product model data exchange is a key element in allowing the use of computer and information technologies to competitive advantage.

SHIPBUILDING AND THE PRODUCT MODEL

The use of computers and information technology in shipbuilding, as well as other industries, has proliferated as the cost of hardware and software has come down. Monolithic mainframe systems have either been replaced or augmented by smaller workstations and personal computers, and they are used for more applications than just developing paper drawings and printing payroll checks.

There has emerged from the implementation of computer integrated manufacturing (CIM) the concept of a product model. As computers, automation, and information technology became more common in engineering, business, and manufacturing, the possibility of a monolithic database to provide integration of these “islands of automation” became the goal of those hoping to enhance their competitive position. This has evolved into the *product model*.

The product model is defined as the complete set of information that describes a particular object over its entire life cycle. Restated, the product model is the body of information or database that represents a product’s design, engineering, manufacturing, use, and disposal.

As the types of data elements in this model become more complex, the problem of storing, retrieving, and using this information for all of the enterprise applications becomes a

significant issue. When the enterprise had a single technology vendor and centralized control of information, integration was less of a problem. The formats for exchange of information between applications in a vertically integrated business was controlled by the enterprise and the information systems department of that business. Many of the formats for information were proprietary or special purpose.

Nevertheless, technology has moved forward with higher performance for less cost. This has allowed distribution of information throughout a business. Manufacturing has its own information resources, as does engineering and the business offices. Further, business practices have changed resulting in more out-sourcing of manufacturing and subcontracting of services. Each of these businesses has its own information systems and resources.

In a sense, all of this information makes up the product model. Business practices revolve around the exchange of information as much as exchanges of physical materials. There is seldom centralized control of technology in an enterprise information systems department. Consequently, there is a need for standardization of information formats to make the exchange of product model data efficient and practical in shipbuilding. The MariSTEP project was conceived to address, and solve, this problem.

THE MariSTEP PROJECT

This project was developed in response to an invitation from the Defense Advanced Research Projects Agency (DARPA, formerly ARPA) to submit a full technical and cost proposal based on the project abstract entitled "Development of STEP Ship Model Database and Translators for Data Exchange Between U.S. Shipyards." In negotiations with DARPA, the team membership was increased to include additional shipyards and vendor participants.

In the interest of the U.S. shipbuilding industry and the U.S. Navy, a consortium of qualified parties was formed to respond to this invitation. This consortium is being led by Intergraph Federal Systems. Other members include :

- Avondale Industries
- Computervision Corporation
- Electric Boat Corporation
- Ingalls Shipbuilding (a Division of Litton Industries)
- Kockums Computer Systems
- Newport News Shipbuilding, and
- the University of Michigan.

The relationship of the shipbuilders and their CAD vendors is demonstrated in Figure 1. Advanced Management Catalyst serves as a facilitator at several meetings during the project.

The objectives of this project are to implement a neutral file transfer capability between the product models at the U.S. shipyards, and to develop a United States marine industry prototype Product Model Database (PMDB) which will facilitate the implementation of translators and product model data architectures by U.S. shipyards and CAD system developers.

Background

The benefits of digital data exchange have been recognized since the advent of computer aided design and manufacturing systems in shipyards. Standards such as the Initial Graphics Exchange Standard (IGES) have been developed to transfer data between existing CAD systems. The advantages of digital data transfer between design agent and shipbuilder were clearly demonstrated on Navy programs such as the Arleigh Burke Class destroyer and the SEAWOLF submarine. However, there is no system used in ship production to transfer a complete set of product model data which would be required to provide a full description of a modern ship.

STEP is an International Standard (ISO 10303) designed to meet the digital data transfer requirements of computer systems in many industries today and for the foreseeable future. Unfortunately, the initial version of this specification (issued in 1994) does not address the needs of the shipbuilding industry, even though there have been concerted efforts since 1986 to incorporate

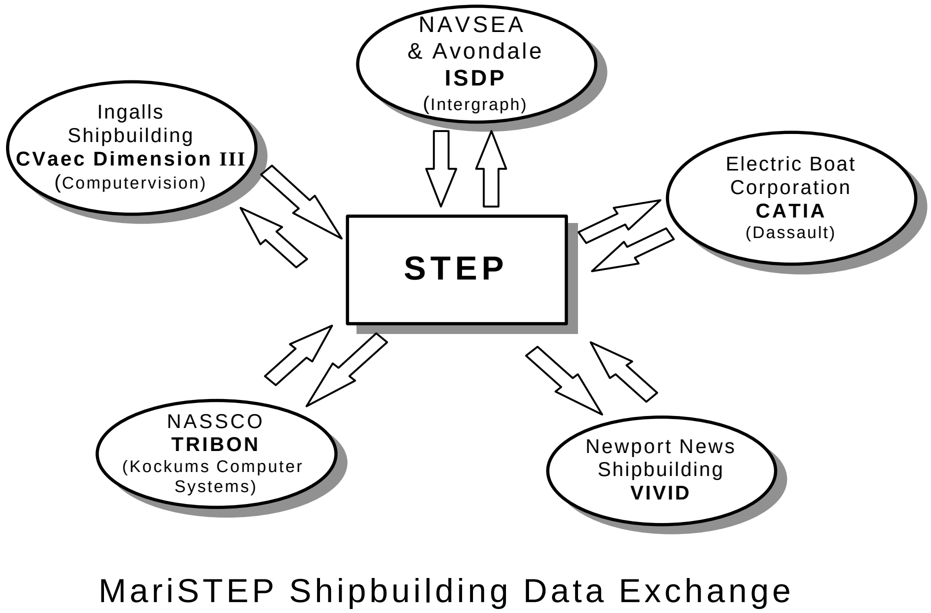

Figure 1 - Typical Data Exchange Paths for Ship Product Model Data

shipbuilding requirements into the development of the standard

NIDDESC (Navy / Industry Digital Data Exchange Standards Committee) was a cooperative effort, begun in 1986, among U.S. shipbuilders and the Navy, whose goal was to have the requirements of the shipbuilding industry reflected in STEP. NIDDESC developed a suite of six Application Protocols (APs) which incorporated the requirements of the shipbuilding industry in STEP format, and delivered these to the International Organization for Standardization (ISO) in 1993.

While NIDDESC was developing Application Protocols in the United States, several efforts were underway in Europe to outline the requirements of shipbuilding for STEP as seen by the European shipyards and regulatory agencies. European initiatives such as NEUTRABAS, MARITIME, and now EMSA have contributed to the STEP development efforts, but have provided a different view of the problem than that addressed by the NIDDESC APs. These many efforts have led to five shipbuilding Application Protocols now being accepted as work items for STEP by ISO TC184/SC4/WG3. These APs represent a combination of the NIDDESC efforts and the various European initiatives.

The MariSTEP program will be the first large scale implementation of the shipbuilding Application Protocols, and its efforts should assist in improving these documents, and should help accelerate their adoption as International Standards.

MariSTEP Vision

At the outset of the MariSTEP project, the team formulated and verbalized a vision for the future, based on the successful outcomes of this project. The premise was that the vision should be a representation of the way the shipbuilding community would be conducting business in the year 2001, as a result of these outcomes.

This is an ambitious five-year projection. It proposes daily use of many processes and capabilities that do not presently exist, or exist only as a rudimentary beginning. It envisions the acceptance of a set of world-wide standards as a U.S. national standard, adhered to by vendors, suppliers, and shipbuilders alike, with a standard mechanism for sharing electronic data to a degree that has never before been possible.

Electronic commerce is the way of the future in many businesses, as in shipbuilding. The MariSTEP project is intended to be the catalyst for this kind of progress and will serve to prototype the means to that end.

The MariSTEP Vision expresses the goals of the project to enable the shipbuilding community to exchange product model data between different shipbuilding information systems without loss of intelligence - easily, quickly, cost-effectively and reliably.

It further specifies that this will be accomplished through the use of a single internationally accepted standard (STEP), enabling shipbuilders, design-agents, owners, operators, regulatory bodies, classification societies, sub-contractors, government agencies and vendors to exchange ship product model data.

Data exchange of pertinent information both within organizations and across organizations supports activities involved in the life cycle of a ship:

- conceptualization
- design
- construction
- testing & evaluation
- training
- repair

- maintenance
- operation
- disposal

Since most of the major U.S. shipyards and their CAD/CAM vendors are represented in the consortium, the MariSTEP project is in a position to provide these enabling technologies to the shipbuilding community, allowing processes to be re-engineered to take full advantage of product model data transfer capabilities. Effective use of these capabilities throughout all levels of the enterprise will allow production and maintenance of quality ships cost-effectively.

The STEP data exchange capabilities will enable the U.S. shipbuilding industry to be a viable competitor in world markets. The prototypes resulting from the MariSTEP project should become the foundation for the shipbuilding data exchange products which will be commercially available in the years ahead.

ACTIVITY AND AP SELECTION

A primary task of the first phase of the MariSTEP project was to determine the scope of product model data transfer to be covered by the implementation prototype. This scoping activity included selection of the primary activities, development of exchange scenarios, and a detailed evaluation of application protocols.

The activities reviewed included those of ship design, construction, and operations life-cycle that should be supported by a prototype product model transfer capability. The exchange scenarios were those between the various organizations involved in the design and construction of a ship which would likely require transfer of product model data. A detailed evaluation was done of the ISO and NIDDESC shipbuilding application protocols to determine which of the standards would provide the most useful product model information to support transfers between the shipyards for the chosen life-cycle activities, and which of the standards were sufficiently complete to allow implementation within the duration of the project.

Activity Selection

During the development of the NIDDESC application protocols, Application Activity Models were created to document the life cycle phases within the ship design and construction process and to illustrate the types of information created during each life-cycle phase which is passed to the succeeding phases. An Activity Model was created for each design discipline by experts from the various shipyards and design agents working on the NIDDESC application protocol project. The Activity Models were documented using the IDEF0 activity modeling methodology.

Figure 2 is a sample Activity Model which was first developed for the NIDDESC Ship Structure Application Protocol. The boxes labeled Feasibility Design, Functional Design, Detail Design, and Production Engineering are the primary life-cycle activities during which product model data is created by an organization,. It is the data from these activities which may need to be transferred to another organization or to another group within the same organization. The outputs from these activity boxes illustrate the types of information created during these primary activities. The information types are the requirements which drove the development of the data models documented in the application protocols. Similar activity models were created as a scoping mechanism for each of the ISO shipbuilding application protocols. The ISO Activity Models were created by the European Maritime Project and deal less with ship design and production and more with the ship design approval process by a classification body, and with ship operations and inspections.

The MariSTEP team evaluated both the NIDDESC and ISO Activity Models to determine which activities and information types should be supported to provide the most benefit to the U.S. shipyards for exchanges between business partners during a particular activity and for “down-stream” transfer to organizations involved in later stages. The primary activities selected for implementation included data developed during the Functional Design, Detail Design, and Production Engineering phases.

EXCHANGE SCENARIOS

To further focus the intended scope of the prototype, the team evaluated various potential exchange scenarios for the collaborative design and construction process that exists in the shipbuilding industry. Historically one organization would be responsible for an entire design or construction phase. However, multifaceted teaming arrangements are employed in shipyards during design and construction to reduce the ‘time to market’ for a new ship, and to more effectively use available design and manufacturing talent in a shrinking industry. The recent bids submitted on the LPD17 proposal demonstrate this new type of teaming arrangement. Figure 3 illustrates various product model exchanges that can be expected within the industry. The activities within the shaded triangle involve those scenarios the team decided to address for the initial prototype. These are exchanges of product model data between a design agent (either independent or within a shipyard organization) and a design subcontractor (also either independent or another shipyard) during either the Functional or Detailed Design phases, between a design agent and a shipbuilder for construction of the design from information produced in the Detailed Design and Production Engineering phases, and between two shipbuilders who might share construction of a single ship or a class of like ships.

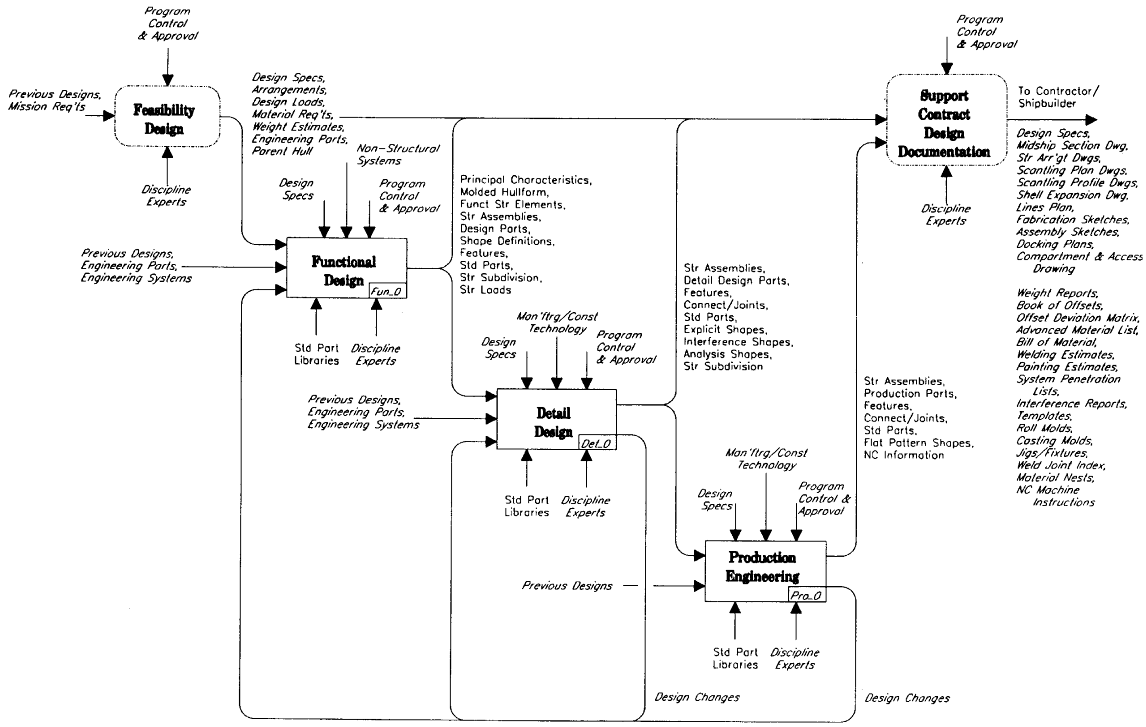

Fig. 1 Ship Structure AP scope

Figure 2 - Ship Structure Activity Model

Evaluating the Application Activity Models and evaluating and choosing industry exchange scenarios helped to focus the team on the scope of product data that would need to be supported by the prototype translators. It also aided in the evaluation of the available information models for determination of the quality and completeness of the existing models and areas that would need to be developed during the remainder of the first phase of the project to produce an implementable schema and would be useful to the participating organizations upon completion of the project.

As part of the requirements definition effort undertaken in the first phase of the MariSTEP Project, a number of exchange scenarios were identified that promised significant benefits. These different data exchange scenarios were then used as guidance as candidate schema modifications were considered, and as the MariSTEP Project Testing Plan was prepared. The translator technology was developed to broadly benefit the ship design and shipbuilding community. *The project scope was biased towards usefulness in transferring information in the design phases where the greatest benefits were, and where it was seen that the greatest volume of product model information was developed and exchanged*. That scope was determined to wholly include detailed design information and much of the information developed during production design, functional design, and preliminary design.

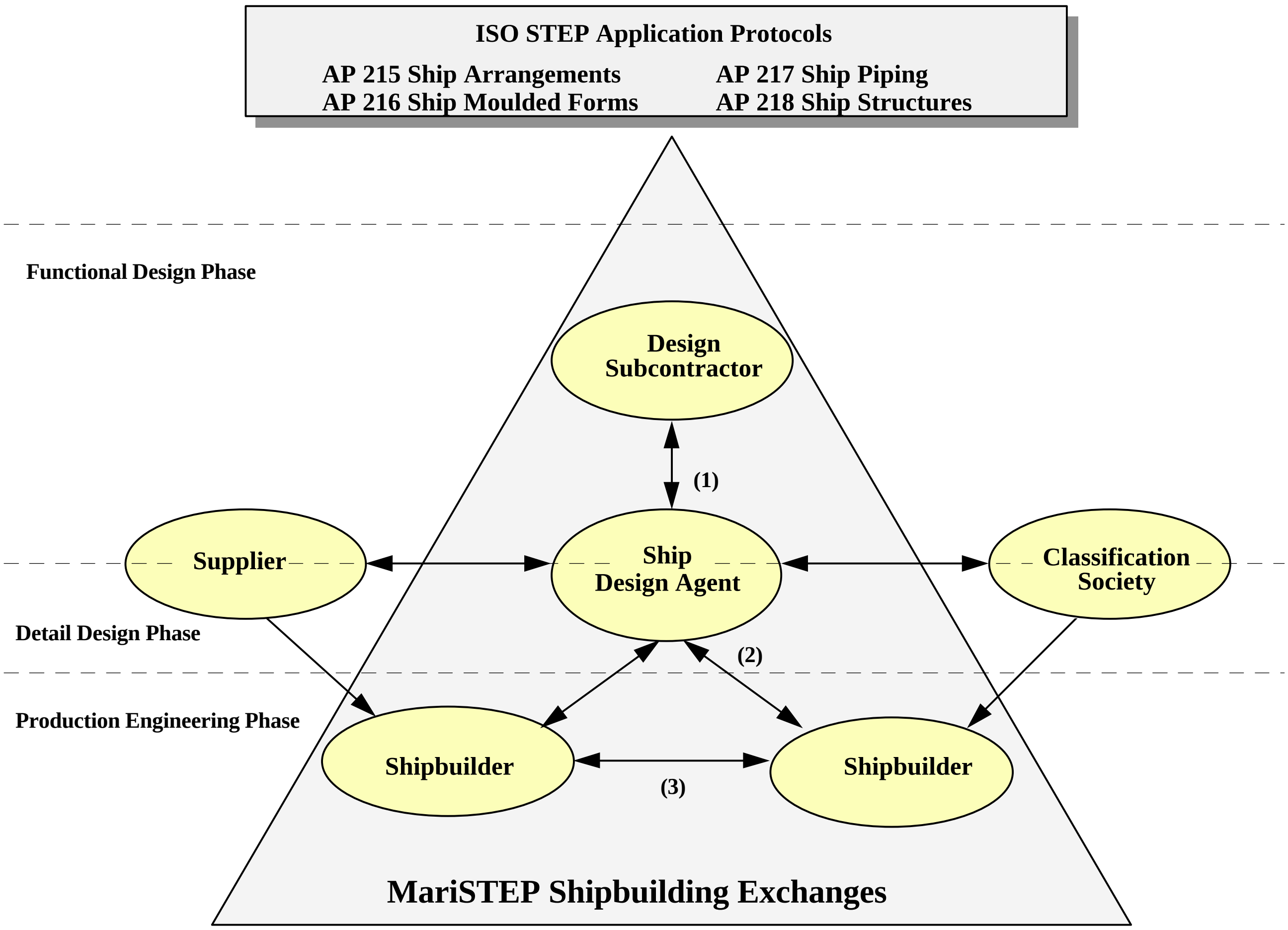

Figure 3 - Typical Data Exchange Paths for Ship Product Model Data

Exchanges were also characterized by the type of information that would typically be transferred. Information content varies with the particular stage of the process as with the type of organization involved. The matrix in Table I shows some of the volume characteristics of the information content that these different exchange scenarios typify.

Design Agent - Shipyard Scenario

The most traditional exchange path for U.S. shipbuilders is the exchange of information between the design organization and the shipyard. This applies in the same way if the design organization is external, as in the case of a design agent, or if referring to the internal design organization of the shipbuilder. The largest volume of information in this scenario is detailed design information describing the hull structure and the arrangement and details of all machinery and outfitting systems included. Information is exchanged during the early stage design for reasons such as the shipyard's build strategy development and other planning purposes, but the volume increases greatly during the detailed design stage as work instructions are developed from the detailed design. This is also the stage of design where the most concurrency is necessary.

There are a number of benefits to the ship design process in having technology that allows the exchange of intelligent ship product models in this scenario. STEP, as a neutral format for product model exchange, enables organizations to work in different design environments. External design agents maintain multiple CAD systems so that they may service the needs of their different customers that usually do not have the same systems. This is also sometimes a reality when the design organization is internal to the shipyard. This is not the most productive or efficient way to operate when training and other infrastructure requirements are considered.

KEY
L = Large Volume of Data to be Transferred
M = Moderate Volume of Data to be Transferred
S = Small Volume of Data to be Transferred

TO FROM	DESIGN AGENT	SUB CONTRACTOR	SUPPLIER	REGULATORY AGENCY	SHIP-BUILDER
DESIGN AGENT	-	L	M	S	L
SUB CONTRACTOR	L	-	S	S	M
SUPPLIER	L	M	-	S	L
REGULATORY AGENCY	S	S	S	-	S
SHIPBUILDER	L	L	S	S	L

Table I - Data Exchange Information Content

Shipyard - Shipyard

Another exchange scenario that has been seen in recent U.S. shipbuilding projects is multiple yard building programs. There may be some differences in the mechanics of this type of arrangement. In the lead-follow yard concept, detail design is accomplished in the lead yard and then transferred to the follow yard during the detailed design phase. Another variation is where the detailed design function is shared by some division of the ship either by physical boundaries (fore-aft, etc.) or by division of systems where each shipyard develops design data which must be passed to the other.

Few U.S. shipyards use the same CAD systems. In recent projects such as the Arleigh Burke Class destroyer and the SEAWOLF submarine, there were significantly large costs associated with special means employed to enable this type of digital information exchange. In each of these projects, very different methods were developed and employed. The exchange products developed for these organizations would be only partially useful in another project because they were tailored to the organizations and systems involved at the time. The STEP standard presents a technology for multiple design organizations to pass such ship product model information in a way that would be understood by an equivalent shipbuilding CAD system without customized translation software.

Other Exchange Scenarios

Although the two exchange scenarios discussed above have the biggest payback, there are numerous other transfers possible in the shipbuilding process which can also benefit from the availability of a product model exchange capability. Among these are :

- Exchanging purchased component data from material suppliers,
- Subcontracting portions of a ship design project,
- Design collaboration between partners;
  - The "Virtual Shipyard" ,
- Purchase or licensing of designs from other shipyards or design agents,
- Internal exchanges between dissimilar internal systems, and
- Design Organization - Regulatory Body

TEST DATA SELECTION

Whereas Task I of the MariSTEP project revolved around determining program scope, Task II involves development of a Product Model Database (PMDB).

The Product Model Database defines ships' systems and assemblies of the building blocks selected for the prototype implementation in STEP format. The primary purpose of the database is to define STEP data which can be used to evaluate translators. The development of the database satisfies a critical requirement to evaluate the application protocols using actual data required for design and construction. Evaluation of the PMDB will also determine the ability of the information to represent ship design and construction data.

Description of the Test Data

The first step in PMDB development is to determine the information to be included in the database. The initial definition of the PMDB is very general with additional detail provided as it becomes available. The goal is to define all of the types of data to satisfy the classes defined by MariSTEP, while minimizing the amount of data. For example, the product model may contain pipes, components, equipment, etc. to define a portion of a system, but not all of the systems required for a complete engine room design will be represented. The objective of the test cases is to exercise a broad range of information while minimizing the amount of data. In order for the data to be acceptable to the participants and non-proprietary in nature, it has been culled from a Navy ship design project, the Engine Room Arrangement Model (ERAM).

Engine Room Arrangement Model Data

The ERAM model is a slow speed diesel engine room

designed to be commercially viable while satisfying the requirements of the U.S. Navy Sealift Program. The Intergraph ISDP suite of ship design software is being used to synthesize the MariSTEP Product Model Database. The ERAM product model data consists of hullform, compartmentation, decks and bulkheads, structure, outfit and furnishings, piping, and HVAC. The hullform is defined for the whole ship. Theoretical surfaces are only defined for the decks, bulkheads, and compartments in the engine room and stack. Plates and stiffeners are placed on decks and major bulkheads. At this stage in the ERAM program, end treatment and cutouts have not been defined. All major equipment has been placed, however, a minimum set of attributes has been defined. Distributed systems are limited to pipelines larger than 50mm (2in) for the major piping systems. Ventilation is modeled in the stack and includes engine and generator exhaust. The model also defines pipe lanes, cableway lanes, and reserved areas for ventilation.

Early Stage Data Exchange

The first version of the Product Model Database in STEP format will be developed directly from the ERAM CAD data. The theoretical surfaces and equipment geometries are provided to the other participants using existing technology such as IGES and DXF. The attribute data is provided as a combination of text files and SQL statements. This will allow each of the participants to begin to develop their native product model databases without having developed STEP translators. Each participant will be responsible for developing specific types of data and translating it to the Product Model Database. Ultimately, a reduced set of test data will be defined as a result of the combined effort.

MariSTEP TIMELINE

The MariSTEP program is a three year effort that was officially kicked off in July, 1996 and is targeted for completion in June, 1999. The program is divided into four tasks, with Task I representing the initial stage of the program and Tasks II, III, and IV following the completion of Task I in April of 1997 and running concurrently through the remainder of the program. The relationship of these tasks is shown in Figure 4.

The initial stage of the program, Task I, focused on defining the scope of the entire implementation effort, beginning with a study of the existing ISO and NIDDESC APs. At the end of November, 1996, the APs for implementation were selected and all shipyard environments had begun to evaluate their own data sets as compared to those requested in the shipbuilding APs. In addition, by the end of December, 1996, the shipbuilding processes to be supported in the exchange were identified. A challenge of this effort was the selection of a subset of data that was rich enough to be meaningful but small enough to be achievable in this limited timeframe.

At the end of January, 1997, the team had identified all aspects of the data exchange and was beginning to define the schema to be used in the implementation phases. The schema(s) must be completed by the end of Task I in order to support the implementation phases of Tasks II and III.

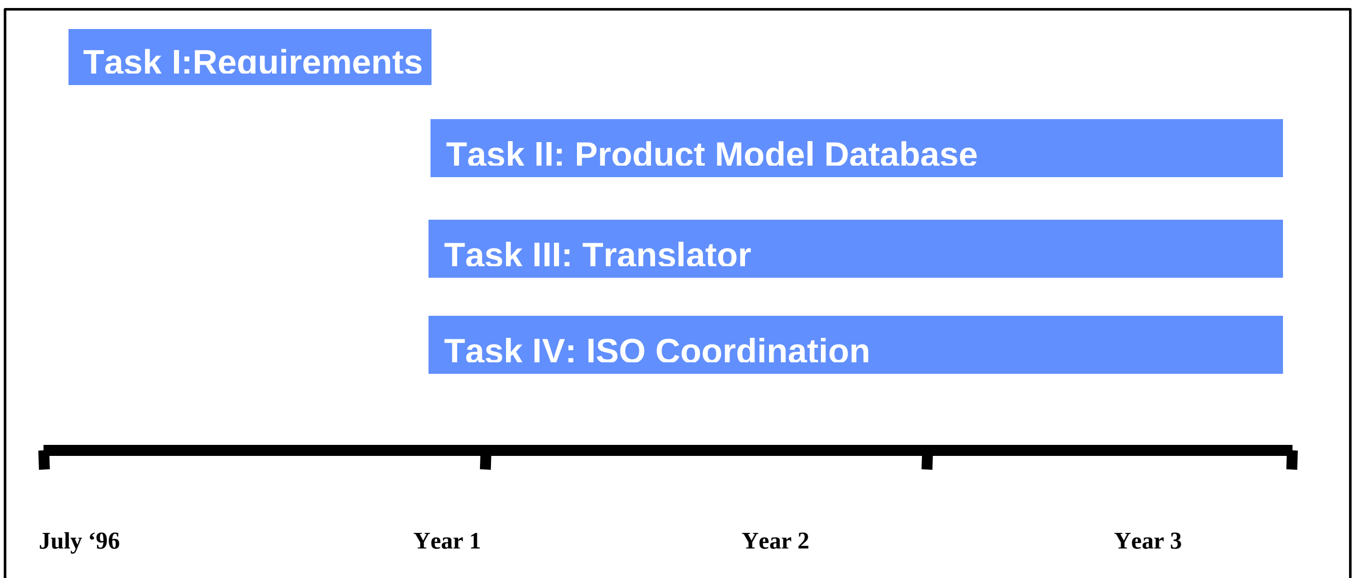

Figure 4 - MariSTEP Timeline

Beginning in May, 1997, Tasks II and III are dedicated to implementation of the data exchange defined in Task I, aiming at

1) creation of a Product Model Database (Task II) which will be used for testing purposes and
2) actual translator implementations for each of the five shipbuilding environments in support of data exchange

(Task III).

Also beginning in May ‘97 is a task to track the ISO APs. This effort will be critical to the effort since a goal will be to assure that any deviations from ISO are factored back into the ISO Draft APs. All issues and deviations from the Draft APs will be documented and submitted to the ISO Committee(s) throughout the program in order to influence the evolving ISO Standards

SUMMARY

MariSTEP is a DARPA / MARITECH sponsored cooperative agreement including the U.S. Navy, major U.S. shipyards, their CAD vendors, and research centers.

It is developing a prototype of a ship Product Model Database allowing ship production data to be exchanged between cooperating yards and the Navy with an integration never before achieved.

MariSTEP is developing processes that enable concurrent design and production among cooperating U.S. yards working on the same ship.

The project is utilizing the ISO STEP Product Data Exchange Standard (ISO-10303) to ensure that U.S. yards can access ship production data from any client in the world, enabling U.S. yards to bid, work, and win in the global shipbuilding arena.

Thus, the MariSTEP program represents a unique opportunity for a diverse group of organizations to work together toward a common goal that will benefit the U.S. shipbuilding industry and further the progress of data standards throughout the world. The project team recognizes the importance of its endeavor and is committed to its successful completion.

For more details about the MariSTEP project and its members, you can visit the web site at :

www.intergraph.com/federal/STEP

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Risk Analysis And Marine Industry Standards

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ABSTRACT

Although the relation of risk and standards is not new, its definition is still unclear. The authors show how a framework established at the University of Maryland for the use of risk-based technology (RBT) methods in maritime regulatory activities could close the gap between risk and maritime industry standards. The authors will consider only one of the system performance characteristics -safety. Although other elements of system performance are equally important, their assessments could be accomplished using a similar framework and risk determination techniques.

INTRODUCTION

The marine transportation industry needs to improve its process and standards for designing the systems, subsystems, and components on which its operations depend. Major improvements in marine designs can only be expected if current processes and standards are greatly enhanced to consider systems engineering techniques capable of assessing risk. Current standard methods of evaluation used in the marine transportation industry are costly, labor-intensive, subjective, and incapable of repeatable and valid results. Programs like U.S. Coast Guard's Marine Safety Evaluation Program (MSTEP) and the University of Maryland's Risk, Safety and Decision for Marine Systems (RSDMS) will demonstrate the value of a better approach. This approach will grow out of proven engineering techniques, that relate well to common everyday problem solving and hazard evaluation processes. One-such process is the basic IPDE (Identify, Predict, Decide, Execute) technique taught by driving instructors to recognize and react to safety hazards on the road.

RISK AND STANDARDS

The relationship between risk and standards is not new and its definition is dependent on the point of view of the observer. To better appreciate this dilemma a closer look at the risk and standards from a historical perspective is needed.

Humanity has always sought to either eliminate or control unwanted risk to health and safety. Industries have achieved great success in controlling risk, as evidenced by advances made building methods for skyscrapers, long-span bridges and super tankers. Yet some of the more familiar forms of risk persist and continue to present a formidable challenge to both government and industry.

Ironically, some of the risks that are most difficult to manage are those that us with the greatest increase in our standard of living. The invention of the automobile, the advent of air travel and space exploration, the development of synthetic chemicals, and introduction of nuclear power all illustrate this point.

The need to help society cope with problems of risk gave rise to an intellectual discipline known as risk management. The complexity and pervasiveness of risk management requires cooperation of specialists from many fields of science and technology to combine their efforts in a holistic manner.

Within the U.S. government a milestone in technological research was attained in 1975 with the U.S. Atomic Energy Commission calling for nuclear reactor safety study, generally known as the "Rasmussen Report." The Rasmussen report was greeted with both great interest and substantial criticism. Some of the criticism involved valid technical concerns, some were adversarial reactions motivated by opposition to nuclear power. To obtain an independent evaluation and deal with the criticism the U.S. Nuclear Regulatory Commission appointed a second committee under the chairmanship of Professor Harold W. Lewis from the University of California. Lewis's report confirmed many of the technical criticisms of the Rasmussen report. However, despite these problems, Lewis concluded that the techniques developed and demonstrated in the Rasmussen study were "extremely valuable and should be far more widely applied in the process of regulating the nuclear industry." He further stated that "probabilistic techniques which provide guidance on the important issues in reactor safety, would be helpful in determining the priorities of the U.S. Nuclear Regulatory Commission both in its safety-research program and in the development of its regulatory and inspection resources." (Lewis, 1980).

When it comes to modern safety standards it is hard to pinpoint their exact origin. When penetrated, the maze of *civilized* trappings that are now part of our daily existence the public finds itself living in an environment devoid of trains, airplanes, skyscrapers, nuclear power plants, and super tankers. A flood of inventions, unprecedented in recorded history, catapulted 19th century society into new and uncharted waters. Spearheaded by engineers, a torrent of new and wonderful machines began to pour into every element of the society. Engineers took pride in the growing superiority of American technology. However, they could not ignore the increasing death and injury statistics attributed to boiler-related accidents. Engineers from the American Society of

Mechanical Engineers (ASME) tackled the problem in 1884 by seeking reliable methods for testing steam boilers. This event marked a major milestone in the development of modern day test standards.

Because technology is being implemented in an ever-increasing pace it is imperative that standards keep pace with new materials, designs and applications. *Today's standard is not the last word, only the latest word*.

UNCERTAINTY TYPES

The analysis of an engineering system often involves the development of a model. The model can be viewed as an abstraction of certain aspects of the system. In performing this abstraction, an engineer must decide which aspects to include and which to exclude. Figure 1 shows uncertainties in these aspects that can make model development difficult. Also, depending on the state of knowledge about the system and the background of the engineer, unknown aspects of the system might substantially increase the overall level of uncertainty. Aspects of the system fall into three categories, i.e., abstracted, non-abstracted, and unknown amongst witch several types of uncertainty can be present. Figure 1 provides examples of uncertainties within each category.

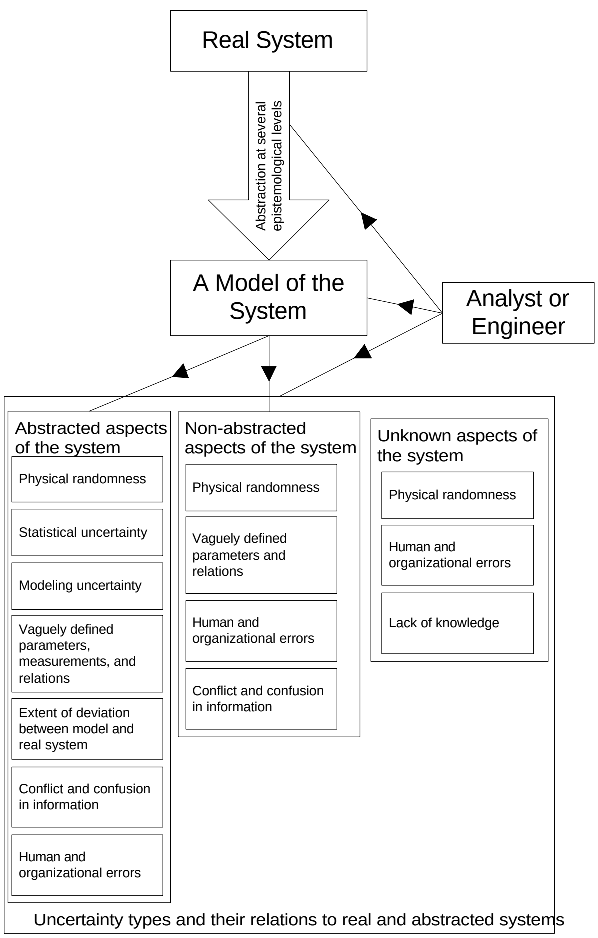

Figure 1. Uncertainty types for engineering systems

Uncertainties in engineering systems are mainly attributed to ambiguity and vagueness in defining design and performance parameters of the systems and their interrelationships. The ambiguity component is generally due to the following sources, which include:

(1) Physical randomness;
(2) Statistical uncertainty due to the use of limited information; and
(3) Model uncertainties that are due to simplifying assumptions, simplified methods, and idealized representations of real performances.

The vagueness-related uncertainty is due to the following factors:

(1) The definition of parameters, e.g., structural performance, quality, deterioration, skill and experience of construction workers and engineers, environmental impact, and conditions of existing structures;
(2) Human factors; and
(3) The inter-relationships between the design and performance parameters of complex systems.

Objective Types

Engineers and researchers normally handle ambiguity and uncertainty in predicting the behavior of engineered systems by using existing theories of probability and statistics. Probability distributions are used to model system parameters that are uncertain. Probabilistic methods that include reliability-based methods, probabilistic engineering mechanics, stochastic finite element methods, and random vibration were developed for this purpose. In this treatment, however, a realization of a subjective type of uncertainty was established. Uniform and triangular probability distributions are often used to model this type of uncertainty. Bayesian techniques have also been used to model these parameters. The underlying distributions and probabilities were then modified to reflect this increase in knowledge. Regardless of the nature of the information, whether it was subjective or objective, the same mathematical assumptions and tools are used.

Subjective Types

Subjective types of uncertainty arise from inconsistencies inherent in human derived abstractions of reality required to simulate complex systems. These abstractions lack crispness and precision. Vagueness is distinct from ambiguity in source and natural properties. The axioms of probability and statistics are limited for this type of modeling and analysis, and may not be relevant. Therefore, vagueness is best modeled using fuzzy logic theory. In engineering, fuzzy logic has to be a useful tool in solving problems that involve this type of uncertainty. For example, these theories have been successfully used in:

- Strength assessment of engineered structures
- Risk analysis
- Analysis of construction failures, scheduling of construction activities, safety assessment of construction activities, decisions during construction and tender evaluation
- The impact assessment of engineering projects on the quality of wildlife habitat
- Planning of river basins

- Control of engineering systems
- Computer vision, and
- Optimization based on *soft* constraints.

CONSIDERATION OF RISK

It is known that “risk” affects the gambler about to roll the dice or the acrobat taking his first jump. But with these simple illustrations aside, the concept of risk comes about due to recognition of future uncertainty -- our inability to know what the future will bring in response to a given action. Risk implies that a given action has more than one possible outcome.

In this simple sense, every action is "risky", from crossing the street to operating a ship. The term is usually reserved, however, for situations where the range of possible outcomes is in some way significant. Common actions, like crossing the street don’t usually imbibe as much risk as complex actions, such as operating a ship. Somewhere in between, actions pass through thresholds that differentiate them as either being low risk or high risk. Figure. 2 below depicts symbolic notions of risk where sailing in a small boat could inherently be more risky than aboard an ocean liner. This distinction, although vague, is important -- if one judges that a situation is risky, risk becomes one criterion for deciding what course of action you should pursue. At that point, some form of *risk assessment* becomes necessary.

$$\text{RISK} = \frac{\text{HAZARD}}{\text{SAFEGURDS}} = \frac{\text{ocean}}{\text{ship size}} = \frac{H}{S}$$

$$R = R_1 + R_2 = \frac{H_1}{S_1} \quad \frac{H_2}{S_2}$$

Figure 2. Symbolic Equations of Risk

Characterization of Risk.

Risk derives from the inability to accurately predict the future, and indicates a degree of uncertainty that is significant enough to be noticed. This definition takes on additional meaning by concidering several important characteristics of risk.

First, risk can be either objective or subjective. The former refers to the definitive product of scientific research. The latter refers to non-expert perceptions of that research, and can be significantly altered by the consideration of whatever is occupying the public mind or body politic at the particular moment in time. This distinction is important in how it characterizes both public opinion and the opinion of experts.

Although it is tempting, and quite common, to attribute disagreements between the public and the experts to public ignorance or irrationality, closer examination often suggests a more complicated situation. Conflicts often can be traced to differences in perspective and definitions such as what the true meaning of risk is and how it applies to the unique circumstances of both camps. When the public proves to be misinformed, it is often for good reason, such as receiving faulty information through the news media or from the scientific community. In some instances, members of the public may have a better understanding of certain issues than the experts, but are unable to draw the right conclusions due to lack of knowledge about the use of existing risk assessment tools.

Along with these objective elements found in public opinion, there are inevitably elements of subjectivity to be found in expert estimates of risk. Standard definitions of objectivity typically refer to the independence of the observer as a critical component. Thus, different individuals following the same procedure should reach the same conclusion. However noble as a goal, this sort of objectivity can rarely be achieved. Particularly in complex areas, such as risk analysis, expert judgment is usually required. Even in those orderly areas for which statistics are available, interpretative questions must be answered before current, or even historical, risk levels can be estimated. This is the case in such circumstances as temporal trends, e.g., whether or not another major oil spill is imminent and predisposed causes, e.g., where questions of crew, or human incompetence need to be addressed. Total agreement on such issues is a rarity. Thus, objectivity should always be an aspiration, but never assumed as a given. When the public and experts disagree, it is a clash between two sets of different opinions. It is important to recognize that experts, differing in their definitions of risk, will also differ in how they acknowledge the role of judgment in risk assessment.

Flipping a coin is an objective form of risk because the odds are well known. Even though the outcome is uncertain, an objective form of risk can be described precisely based on theory, experiments, or common sense. Most agree with this description of objective risk. Describing the odds for thunderstorms to develop on any given day is not as clear cut, and represents a subjective form of risk. Given the same information, theory, and computers, etc., one weatherman may think the odds of thunderstorms are 20% while another weatherman may think the odds are 50%. Neither is wrong. Describing a subjective risk is open-ended in the sense that one could always improve the assessment with new data, further analysis, or by lending more credence towards other professional opinions. Most risks are subjective, and this has important implications for those assessing risk or making decisions based upon risk assessments.

Deciding that something is risky often requires personal judgment, even for objective risks. For example, one flips a coin and wins $1 if its heads and loses $1 if its tails. The personal risk of winning $1 or losing $l would not be overly significant to most people. However, if the stakes were much higher (e.g., $10,000), most people would find this situation to be quite risky. There would still be a few individuals who would not find this range of outcomes to be significant, but the majority of individuals would probably find it intolerable.

Most people differ in the amount of risk they are willing to take. For example, two individuals of equal worth may react quite differently to the $10,000 coin flip. People will differ widely in their preferences, or tolerances, for risk primarily due to their unique set of personal experiences and current station in life.

Defining Risk Analysis

Risk analysis is the process of evaluating the degree of risk inherent in a particular situation a pre-established set of criteria. There is consensus among experts that a comprehensive risk

analysis consists of three major components: risk assessment, risk management, and risk communication.

Risk assessment is essentially the process of deciding how dangerous a hazard is. The first step in the process of risk assessment is to identify and qualitatively describe the hazards within a given situation that are to be assessed. Next, the level of exposure to the hazardous activity is assessed. Along with that the response of the people and systems in question is assessed to different hazard intensity levels. Finally, the above information is combined to characterize the risk in quantitative terms. While no risk assessment is devoid of value judgments, the task should be as objective and consistent as possible.

Risk management is the process of selecting alternatives and deciding what to do about an assessed risk. Risk management, unlike risk assessment, involves consideration of a wide range of factors including: engineering, economic, political, legal and cultural aspects pertaining to the specific hazardous condition in question.

Risk communication is the process by which organizations and individuals exchange information about risk. Because perceptions of risk and its consequences, often differ widely, risk communication typically requires a heightened level of sensitivity and mutual respect between all parties involved to ensure that a genuine dialogue exists and can be maintained over time.

Qualitative vs. Quantitative Risk Assessments

The controversy surrounding the use of quantitative vs. qualitative risk analysis methods is not new. The Center for Building Systems and Technologies located at the University of Maryland recommends blending of the two methods. The qualitative analysis can always be made more quantitative by defining probabilities in a more numeric manner if sufficient data exists. The quantitative analysis can always be simplified if discrete levels of risk and reliability are substituted for actual numeric values. In many real-world circumstances this type of blending technique is the only way to satisfy the requirements of various stakeholders while operating in a less than ideal data environment.

Furthermore, preferred hazard controls or system safeguards can only be matched to the risk level if an initial quantitative analysis is done. Therefore, in most cases a certain level of both qualitative and quantitative analysis is required to fully comprehend the inherent risk within a specified system. No matter what method is used, it is important to view the entire system as a whole and not simply as a number of unrelated pieces or components.

A top-down scenario-based qualitative approach is advocated for initial risk assessments involving the maritime industry. This allows the industry to focus its remaining resources on quantitative assessments of those marine systems that are the primary contributors to safety at sea. Based on general experience and readily available information the qualitative analyses are first performed to identify hazard scenarios, and to categorize these scenarios on the basis of likelihood and consequence. The output of this first step is a priority ranking of hazard scenarios and recommended actions that address each risk category.

As a second step, quantitative risk assessment (QRA) of selected scenarios may be necessary to refine the understanding of the most significant contributors to risk, and to provide an adequate basis for recommended actions, as in the form of design or operational enhancements to mitigate or control the underlying risk. In most cases the collection of data for quantitative analysis will begin once the results of a qualitative assessments are available and a reasonable safety management and communication effort are underway. The output of this step is (1) a quantitative definition of the absolute and relative risks, with explicit treatment of the underlying uncertainty. In addition, a more rigorous definition of the major contributors to risk is also obtained. The combined results provide an understanding of the benefits and costs of various risk-reduction alternatives. This is the essence of MSTEP's risk assessment logic engine, the Engineered Marine System Assessment (EMSA) methodology, being developed at the Center for Building Systems and Technologies at the University of Maryland. As shown in Figure 3, EMSA is built around an iterative process of risk assessment and risk management techniques in which both qualitative and quantitative methods are used to provide a logical basis for balancing risk and economic considerations.

Quantification of risk is as much a process of identifying what is known as it is of quantifying what is unknown. With respect to EMSA, quantification of marine risks must be achieved using less-than-perfect data. Thus, in quantifying frequency of occurrence and consequences, it is necessary to compile all forms of evidence, e.g., historical evidence, expert opinion, and experience with similar systems or events. Finally, the results are presented in a manner that makes them explicit in terms of an in-depth understanding of the underlying risks. Unfortunately, for the maritime industry, the likelihood of having collected the right types of hazard-related data prior to establishing a risk management program is extremely low. Hopefully, this will not be the case in the future as the industry migrates to risk-based forms of safety assessments.

STANDARDS AND CRITERIA

Although the dictionary indicates a number of applicable meanings to the word "standard," only two are

relevant here; one, as the basis for measure of physical properties, and two, as the norm for common or accepted practice.

In the United States, the phrase of *laisse-faire*, or freedom of choice coupled with a lack of uniform standards continues to have considerable negative impact on safety and economic viability of U.S. marine industry. An example of this is the fact that most of the world uses the metric system while the United States still uses the English system, thus condemning U.S. products to suffer under the banner of having-poor integration qualities.

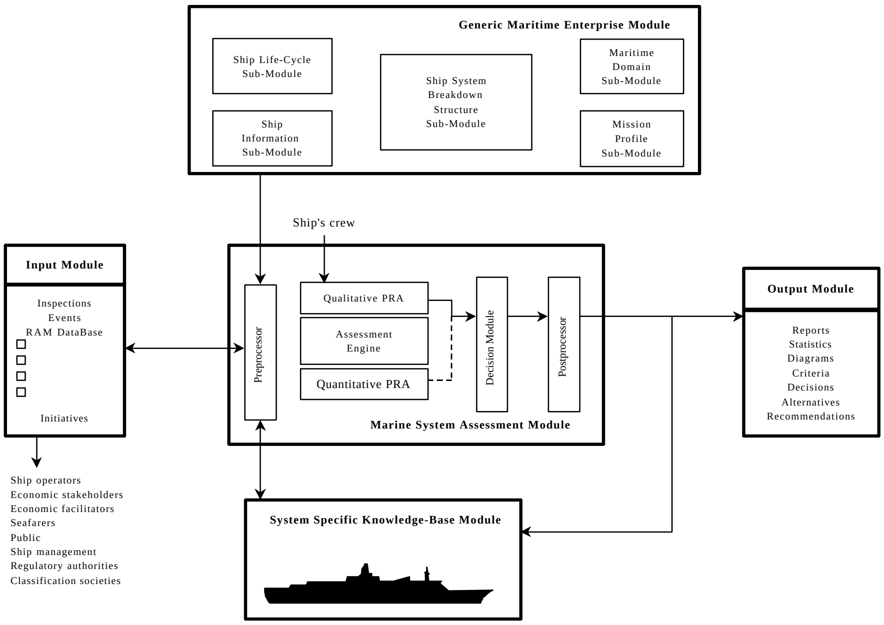

Figure 3. Engineered Marine System Assessment (EMSA) Methodology (Karaszewski et al 1992)

with systems built elsewhere in the world. In other industrialized countries, the use of uniform standards has avoided most of the problems currently being experienced in the United States. These standards not only improve safety but also reduce the costs of these products and affect the entire value chain associated with these products within their native economies In addition, these uniform standards allow greater flexibility in making improvements, regardless of whether they are government-mandated or market driven.

Objection to Standards

The United States is extremely cautious in setting or adopting standards, especially those of a mandatory nature. This is the result of a national paradigm that is heavily influenced by tradition and upon the belief that standards lead to inferior quality products and obfuscate the market's ability to exercise freedom of choice. Unfortunately, this is still the way that many U.S. managers feel when they have to meet requirements set by mandatory standards. Imposition of requirements, irrespective of their true merit, is frequently met with great amount of reluctance. This is primarily due to the level of effort it takes to understand the basis for these requirements and assimilate them into their existing processes. The new criteria are perceived as being inconvenient, and subject to creating delays or adding costs. Modern U.S. management also treats the integration of mandatory standards as a collateral duty for its line managers thereby downplaying their significance to the organization and more importantly to the marketplace. In many instances, failure to meet these mandatory requirements has also resulted in litigation. For these reasons, designers and managers prefer voluntary standards since they can be ignored or accepted at the discretion of each individual organization without any fear of future legal entanglements. In this voluntary mode of standards implementation, managers are accepting on behalf of their organizations what they believe to be a low probability of a serious casualty occurring while averting the intent and spirit of rigorously developed standards. Just how much risk is

being assumed in this manner is hard to establish. However, it is fairly plain to see that this form of risk management is extremely shortsighted. It represents a form of professional procrastination and a meager attempt to forestall the inevitable both of which are not healthy indicators of world-class statue and performance.

Benefits of Standards

Putting aside the reasons for imposing voluntary or mandatory standards, recognition of standards is beneficial to engineers and the public in many ways. A standard often contains useful technical information that engineers will find helpful. A standard promotes consistency and identifies basic levels of safety and dependability in similar systems, equipment, materials, or operations. It helps eliminate the need to search for information that is already resident in the standard, through rigorous screening and incorporation of past experiences. The criteria, or requirements, found within standards were developed to avoid the recurrence of undesirable events or hazardous circumstances that had the potential to cause accidents. Through careful consideration standards were prepared to avoid situations that could develop into problems. Only through careful consideration can the appropriate precautions be taken. In many cases, standards often indicate to designers what should *not be done*. Standards help decide whether a proposed design is safe or not, and assist in making decisions regarding the selection of hazard controls. They help reduce differences in opinion between engineers, manufacturers, regulators, and others concerning levels of safety, types of equipment to be used, mitigation measures to be observed, and safeguards to be incorporated. Potential benefits in the use of standards are:

- Reduction of accidents.
- Maintenance of acceptable levels of safety.
- Establishment of acceptable industrial practice.
- Reduction of legal actions.

Standards and the Courts

The significance of standards when applied to matters of marine safety, is normally that of an indicator of whether the actions of a specific party have been negligent with respect to established levels of safety. Regulators have indicated that a judicious person will normally adhere to rules, processes and procedures that conform to an acceptable level of safety. This acceptable level of safety, in most cases, is what others believe to be a normal or acceptable level of conduct within the recent past. Violation of that acceptable level of conduct may lead the regulators to assume that under the known conditions, there had been negligence on the part of the offender. This assumption leads to a determination of whether or not the performance of the accused has been less than acceptable and had relied on proper foresight and consideration of other parties to avoid injury and property damage. Even less prudent, and liable for criminal punishment, are those who fail to meet a required standard of conduct through violation of a mandatory rule set forth for the protection of public safety, as in the case of U.S. Coast Guard regulation.

A standard to minimize the number of steam boiler accidents was needed, but it was not until early 1900's that such a standard was produced, and the standardization of the design, production, operation, maintenance, inspection, and testing of pressured products was finally accomplished. The standard, in this case called a code, generated by the American Society of Mechanical Engineers (ASME), has been considered one of the foremost achievements of U.S. engineering.

FRAMEWORK FOR APPLYING RISK-BASED METHODS IN MARITIME STANDARDS

The purpose of the framework is to provide a general structure to ensure consistent and appropriate application of Risk-Based Technology (RBT) methods. The principal parts of the framework, are identifying standards applications amenable to the use of RBT, addressing deterministic considerations, addressing probabilistic considerations, and integrating all of these elements. The first two parts are relatively well established. The principal focus of the CBST's present effort is the development of the probabilistic considerations and integration of the deterministic and the probabilistic portions.

Conceptual Structure

As demonstrated by MSTEP the deterministic approach contains implied elements of probability or qualitative risk considerations from the chosen scenarios to be analyzed as design-basis scenarios.

RBT methods like Probabilistic Risk Assessment (PRA) address a broad spectrum of initiating events by assessing the event frequency. Mitigating system reliability is then assessed, including the potential for multiple and common cause failures. Therefore, the treatment goes well beyond the single failure requirements in the deterministic approach. The probabilistic approach to standardization is, therefore, considered an extension and enhancement of traditional standardization or regulation by considering risk in a more coherent and complete manner. A natural

outfalling of the increased use of RBT methods and techniques in shipbuilding is the focusing of standardization efforts on those items most important to productivity, in comparison to current efforts by the regulators of maritime industry to focus strictly on those items most important to safety. Where appropriate, RBT can be used to eliminate unnecessary conservatism and to support additional standardization requirements.

Deterministic-based regulations have been successful in protecting the public health and safety and RBT techniques are most valuable when they serve to bolster the traditional, deterministic-based regulations and support the defense-in-depth philosophy.

The RBT plan defined by the Center for Building Systems and Technologies, among other items, leads the staff efforts to convert this conceptual structure into practical guidance for the maritime industry using RBT in the formulation of maritime regulations. Key items in the plan to use RBT in maritime regulation development include the following identification of roles:

<u>CBST, U.S. Navy, and USCG</u> will develop decision criteria and in performing pilot studies of risk-based concepts for specific regulatory initiatives. CBST staff has received a number of ship-specific and system-specific requests from the U.S. Navy and commercial maritime interests for approval actions based on the findings of probabilistic risk assessments that will be used as pilot studies.

<u>U.S. Navy and USCG</u> will develop guidance for using RBT, in concert with decision criteria development work being performed efforts of above item. One element of the USCG's role is to develop a framework for risk-based regulations and RBT standards development.

This framework will be used in conjunction with ongoing proof-of-concept studies to provide an expert knowledge base capable of sustaining the use of RBT in a broad spectrum of industrial and regulatory activities. The framework described below is intended to ensure consistent approach towards the modification of existing standards and new regulatory decision-making processes. The resultant products will provide an in-depth understanding of each application thereby ensuring that consistent decisions are made.

The proposed framework has four parts:

(1) <u>Identification of both ongoing domestic and international regulatory activities</u>. The framework will allow to define those regulatory application areas in which RBT can play a role in the marine industry's decision-making process. These applications will be grouped by the expected level of RBT sophistication required. As necessary, these groups will be refined as new information and experience is available.

(2) <u>Categorization of problem areas to be addressed by deterministic approaches.</u> It is important to assure that current deterministic approaches are modified only after careful experimentation and review. Factors to be considered will include: the use of engineering principles based on research, test and analysis; the quality of the ship design, the ship production process and build strategy, operation and maintenance procedures; and the use and enforcement of appropriate codes and standards.

(3) <u>Categorization of problem areas to be addressed by probabilistic approaches</u>. There is a need to evaluate the probabilistic risk assessment issues in support of proposed regulatory actions within each application area. Key elements of this approach include:

- Use of established RBT methods (e.g., logic models, statistical analysis;
- Use of human and equipment reliability data from experience, testing and research;
- Use of appropriate scope and level of detail (e.g., modeling of accidents and mishaps);
- Uncertainty analysis; assurance of the technical quality (e.g., through review and approval by expert panels, peers or regulatory agencies); and
- Selection of appropriate risk metrics (e.g., oils spill frequency, amount of oil spilled, frequency of emergency shutdowns).

(4) <u>Integration of deterministic and probabilistic approaches</u>. A consistent and logical integration of the probabilistic and deterministic approaches is needed. The integration process may involve a reassessment of the bases of existing requirements. Such a reassessment would have access to a much-enhanced technical knowledge base in comparison to the one used to initially formulate the requirements. It would also take advantage of risk insights derived from recent probabilistic risk assessments. Successful completion of this portion of the process requires to have expert knowledge of both deterministic and probabilistic approaches. To accomplish this, University of Maryland in cooperation with the U.S. Coast Guard and the U.S. Navy has developed a six-step approach. The steps are listed below and illustrated in Figure 4.

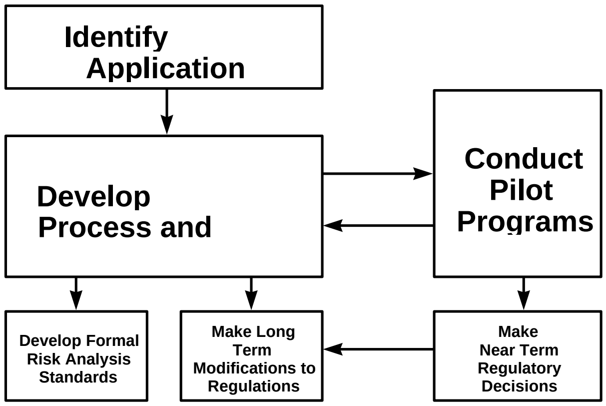

Figure 4. Six-step Process Associated with the RBT Methods in Maritime Standards Work.

(1) Identifying specific applications,
(2) Conducting pilot projects,
(3) Developing and documenting an acceptance process and criteria,
(4) Assisting the maritime industry in making near-term standards and regulatory decisions,
(5) Developing formal RBT standards, and
(6) Making modifications to existing standards and regulations as required.

Throughout this process, active participation of interested members of the public and industry are solicited.

Applications Receiving Industry Support

The process described above is being executed for a number of applications in parallel. One of these applications is the development of reliability-based design rules for ship structures. The development of a methodology for reliability-based design of ship structures requires the consideration of the following three components: (1) loads, (2) structural strength, and (3) methods of reliability analysis. Figure 5 (Ayyub et al 1995) shows an outline of a suggested methodology for reliability-based design of ship structures. Two approaches are shown in the figure: (1) Direct reliability-based design, and
(2) LRFD (load and resistance factor design) sheets. The three components of the methodology are shown in the figure in the form of several blocks for each. Also, the figure shows their logical sequence and interaction. The first approach can include both Level 2 and/or Level 3 reliability methods. Level 2 reliability methods are based on the moments (mean and variance) of random variables. Whereas, Level 3 reliability methods use the complete probabilistic characteristics of the random variables. In some cases, Level 3 reliability analysis is not possible because of the lack of complete information on the full probabilistic characteristics of the random variables. Also, computational difficulties in Level 3 methods sometimes detract from their uses. The second approach (LRFD) is called a Level 1 reliability method. Level 1 uses reliability-based safety factors; but the method does not require an explicit use of the probabilistic description of the variables.

The two reliability-based design approaches start with the definition of a mission and an environment for a ship. Then, the general dimensions and arrangements, structural member sizes, scantlings, and details need to be assumed. The weight of the structure can then be estimated to ensure its conformance to a specified limit. Using an assumed
operational-sea profile, the analysis of the ship produces both a stochastic stillwater and wave-induced responses. The resulting responses can be adjusted using uncertainty-modeling estimates that are based on available full-scale or large-scale testing results. The two approaches, beyond this stage, proceed in two different directions.

The direct reliability-based design approach requires performing analysis of the loads. Also, linear or nonlinear structural analysis can be used to develop a stress frequency distribution. Then, stochastic load combinations can be performed. Linear or nonlinear structural analysis can then be used to obtain deformation and stress values. Serviceability and strength failure modes need to be considered at different levels of the ship, i.e., hull girder, grillage, panel, plate and detail. The appropriate loads, strength variables, and failure definitions need to be selected for each failure mode. Using reliability assessment methods, failure probabilities for all modes at all levels need to be computed and compared with target failure probabilities.

The LRFD sheets approach requires the development of response (load) amplification factors, and strength reduction factors. The development of these factors is shown in Figure 6 (Ayyub et al 1995) using a reliability analysis that is called a calibration of design sheet. Figure 5 shows the use of these factors in reliability-based design. The load factors are used to amplify the response, and strength factors are used to reduce the strength for a selected failure mode. The implied failure probabilities according to these factors are achieved by satisfying the requirement that the reduced strength is larger than the amplified response. The LRFD can, therefore, be used by engineers without a direct use of reliability methods. The background reliability effort in developing these factors is shown in Fig. 6.

The above two approaches require the definition of a set of target reliability levels. These levels can be set based on implied levels in the currently used design practice with some calibration, or based on cost benefit analysis. Also, the consequence aspect of risk can be considered according to this method by using different target reliability levels that are linked to corresponding consequence levels. Additional details on this application are provided by Ayyub et al (1995).

Related Industry Activities

The maritime industry has a number of efforts underway which directly relate to the work being done at the University of Maryland. Among them is the International Maritime Organization FSA (Formal Safety Assessment) methodology and the U.S. Coast Guard's MSTEP (Marine Safety Evaluation Program). The FSA is aimed at the support of IMO's standards development process. A new organizational unit of the U.S. Coast Guard known as the National Maritime Center is performing MSTEP, the largest of these programs. The impetus for MSTEP was the need to address industry's requests for repeatable safety determinations and consistent regulatory process reforms

and improvements.

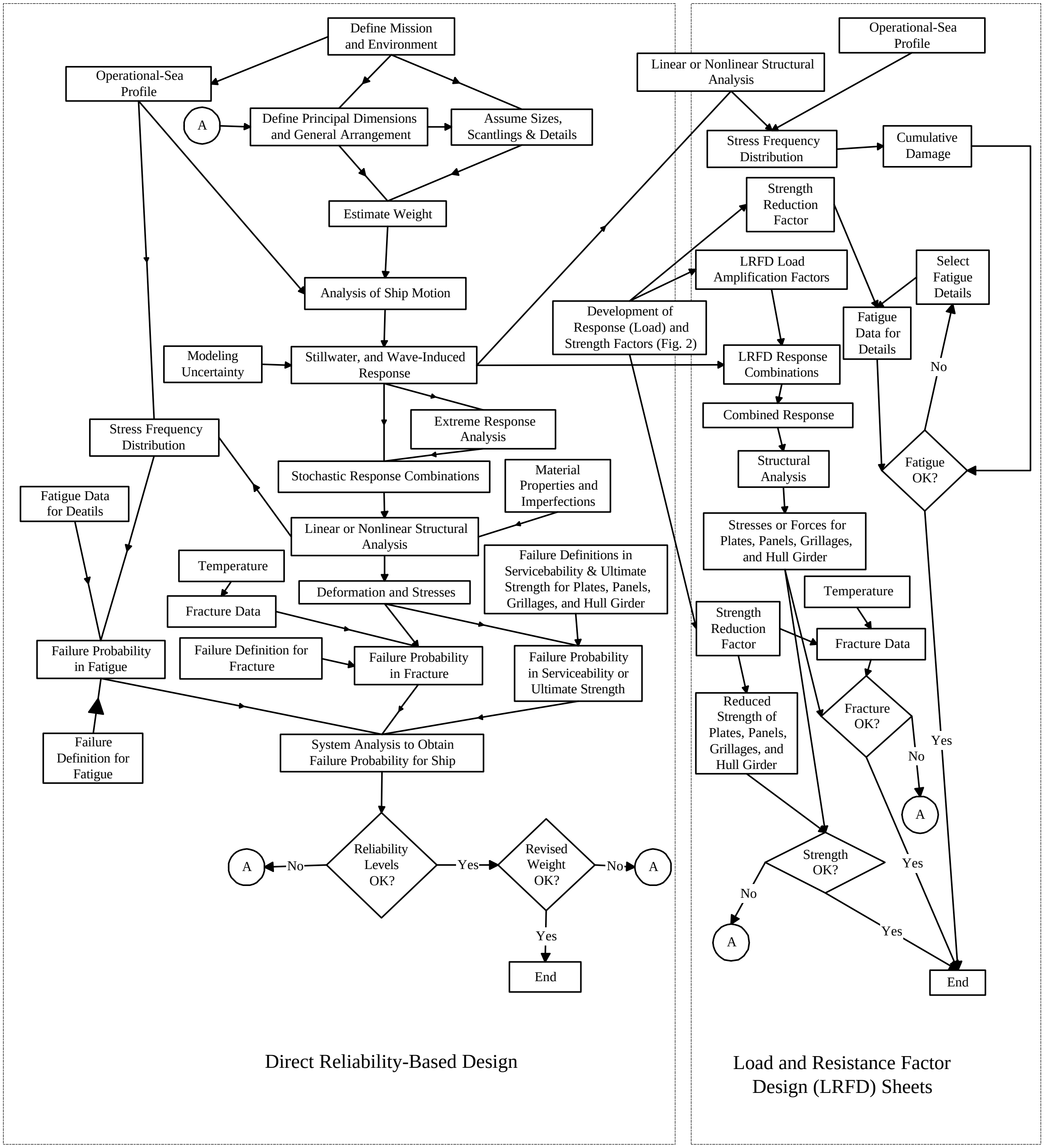

Figure 5. Reliability-Based Design of Ship Structures (Ayyub et al 1995)

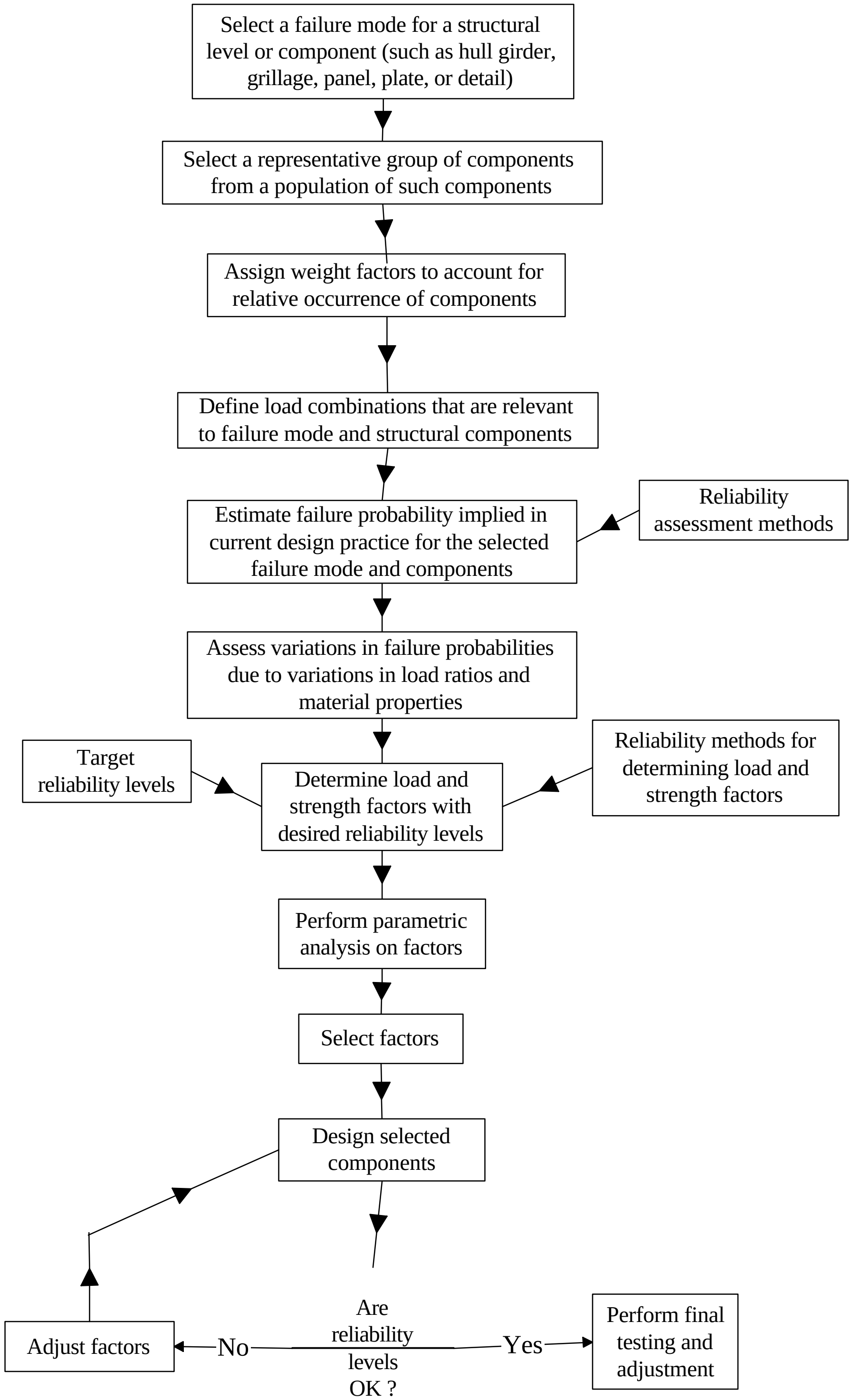

Figure 6. Calibration of Design Sheets (Ayyub et al 1995)

The MSTEP is a new initiative advanced by the U.S. Coast Guard and marine industry. MSTEP has far reaching implications, not only to the industry but to the government as well. Once fully developed, MSTEP will provide industry and government with the ability to further improve their safety assessments for equipment and shipboard systems and allow for proactive regulation reform, development and application.

Initially, one view of the MSTEP concept was that it was a process for applying design and engineering criteria found in existing international marine standards to U.S. marine equipment. This was a rather narrow view. A broader view has now been taken that encompasses a robust systems design and engineering assessment capability. This approach will allow for the formulation and of system-based safety assessment capability. Also, it will allow for the formulation, application, assessment, modification, maintenance and storage of system-based safety criteria for consideration throughout the life cycle of the ship.

RISK-BASED STANDARDS

The transition of the marine industry to risk-based standards will take place gradually. If the observations of the nuclear power industry are any indication the greatest burden to the marine industry, at least in the short term, may be found in the duality of trying to apply both existing practices and RBT methods simultaneously. The most important factor for success will be the commitment that the marine industry and its regulators have towards changing in the direction of risk-based standards. What is needed to aid this process is the basis for measuring the progress of the industry towards its risk-based goals. In addition, the industry must devise a series of mechanisms for demonstrating that its compliance with these goals attains a level of safety that will be approved by its regulators.

With the advent that risk-based assessments will be available throughout the industry and the government there is a need for consistent decision criteria that accept such results as a form of alternative compliance. There is a need for action to be taken by the marine industry and its regulators to establish the basis for risk-based acceptance criteria. This may be achieved by forming regulatory review groups that will conduct a review of existing marine regulations with an eye towards reducing unnecessary regulatory burden by adopting risk-based results as a sustainable alternative.

The University of Maryland is at the forefront of identifying quality assurance, in-service inspection and testing criteria necessary for the formulation of a comprehensive marine standards development plan based on proven RBT concepts. In addition, the university is involved in providing source material and recommendations on the use of RBT methods relating to risk-based standards to the U.S. Coast Guard.

These efforts are aimed at building a clear consensus on the merit of a risk-based standardization process. While the advantages of RBT have already been demonstrated to the government and industry, there remains reluctance on the part of the bureaucracy to mandate risk- compliance as an acceptable alternative for all current and future federal regulations.

LESSONS-LEARNED TO DATE

The need to assess safety risk resulting from shipboard hazards has focused attention in recent years on collection and interpretation of operational data. Operational risk assessments are used to determine the need for safety actions and to communicate to the industry the significance of risks from exposure to hazards. They may also be used to determine the effectiveness of actions taken to reduce risk. Standards and guides for assessing marine risk are being currently developed, most notably by the U.S. Coast Guard with support from the U.S. Navy's Mid-Term Sealift Program. Generally, risk assessment practices are determined by a combination of factors including scientific and technical knowledge, the level of experience of risk assessors, specifics of the system under analysis, industry concerns and marine regulations and guidance.

There are at least two competing factors associated with the application of risk assessment that have encouraged activities at the U.S. Coast Guard and the U.S. Navy. First, it is generally useful and prudent to standardize technical practices of risk assessment process. Standardization of risk assessment methodologies would enhance uniformity, consistency, and communication of policy issues. For example, a standard defining an acceptable increase in the lifetime risk of hearing loss resulting from exposure to shipboard noise is a policy issue. Second, it is often necessary to adjust the risk assessment process to local or regional conditions associated with the potential marine hazards. Numerous shipboard system types, operational schemes, and variety of cargoes can have an impact on the overall assessment of the ship safety.

The challenge for maritime community is to develop standard guides and practices that have enough flexibility to accommodate both factors. Because of the complexity of marine risk assessments and the need to consider risk to human health and the environment, a multidisciplinary approach is essential. Risk

assessment of marine hazards is not a technical discipline itself but requires expertise from numerous technical areas. For example, a few of the disciplines that may be required include psychology, chemistry, statistics and toxicology. Although human health and equipment hazard risk assessments can be and often are developed separately, some amount of information to support them may be the same, and decisions concerning actions to be taken can be influenced by both.

Several project teams made of industry, government and academia are actively involved in developing guides and practices relevant to shipboard hazards. Among them are MARAD's RO/RO Cargo Hold Lighting analysis team, U.S. Coast Guard's Diesel-Generator analysis team, MAN's Four-Stroke and Two-Stroke Diesel Engine analysis teams, and SIEMEN's Shipboard Electric Power Generation Systems analysis teams. The U.S. Coast Guard in cooperation with the Mid-Term Sealift Program Office and the American Society of Mechanical Engineers (ASME) held a Risk-Based Technology (RBT) Workshop in December of 1995. It included members of the marine safety consulting, regulatory, ship classification, academia and industrial community. The majority of the participants agreed that the marine risk-based standards should address both the equipment (systems) and human factors risk assessments.

Since the first marine RBT workshop the U.S. Coast Guard has identified topics from which standard guides and practices are being developed. Several topics regarding marine risk assessment where standards are under development are Preliminary Hazard Assessment (PrHA) of Diesel-Generator System, PrHA of Four-Stroke Diesel Engine System, PrHA of Two-Stroke Diesel Engine System, and a set of PrHAs of Shipboard Electric Power Generation Systems. The PrHA is a top-down approach that defines the hazards, accident scenarios, and risks of a particular process or system. Its purpose is to develop a rank-ordered list of major risk contributors to the system under study. The results from applications of the PrHAs allow management to concentrate their efforts and resources on those areas that have the highest consequence and frequency of hazard. It provides management with a logical basis for balancing the safety risk and economic impact of regulation. These activities are closely coordinated with the industry, U.S. Coast Guard and the major sponsor – the U.S. Navy. A primary goal of the Navy's Mid-Term Sealift Program has been to provide the U.S. Coast Guard and the marine community with a forum and resources so the marine risk assessment issues can be openly addressed by all members of the risk assessment community and new risk-based standards and standard development methods can be evolved.

The major intellectual advancement, or revelation, made by Navy's MTSSTDP Global Standards task on behalf of the marine industry is that the current state of the art for assessing risk of shipboard systems consists of adopting existing forms of failure mode analysis to individual pieces of equipment in complex system environment. In many cases this approach is not capable of assessing risk factors associated with system linkages, both mechanical and operational, and thereby doesn't adequately simulate a real operating environment for these systems. In addition environmental factors such as temperature, humidity, air quality, vibration and noise cannot be factored into existing risk assessment tools. This is evidenced by the controversial study provided by the Japanese classification society, NKK, published in 1995, that attributed the high incidence of engine room fires on oil tankers to vibration-induced failure of fuel oil line joints and couplings.

Advances acceptance on the part of classification societies for individual components of shipboard systems without any ability to place, or simulate, the component within a 'real' system environment where as many operational conditions are accounted for as possible will invariably lead us to the wrong conclusion pertaining to the primary risk contributors within shipboard distributive systems. This was evidenced by several NSRP projects that intended to get U.S. Coast Guard 'pre-approval' of individual system components for use in future commercial shipbuilding designs without any consideration of where the true risks resided within typical shipboard system designs in which these components will reside. For example, pre-approval of electrical switches within a system where the valves are truly the high risk component will gain no increase in overall system safety and only serve to increase system costs. Early qualitative ship-wide system assessments can avert this situation from accurring as was evidenced by the MARAD sponsored RO/RO cargo hold lighting system investigation. Until computers are capable of simulating all operational and environmental aspects of complex marine systems shipboard operational data will remain as the singularly most important element in the proper formulation and execution of these early ship-wide system risk assessments.

CONCLUSIONS

The maritime industry realizes that there is a need for guidelines and standards on the selection, design and operation of shipboard systems. The task of writing such standards, however, is difficult because there are two separate coalitions regarding the analysis of such systems. Differences of opinion, regarding how risk is measured, how system performance is measured, and how the two can be related, makes widespread standardization impractical. Part of the current industrial dilemma focuses on both the qualitative and quantitative methods of assessing risk. To further cloud the picture both offer benefits as well as drawbacks. Qualitative methods offer easily understood "cook-book" results, but the intuitive and subjective process result in considerable differences by virtually all who use it. Quantitative analysis on the other hand requires more engineering manpower and provides a more common ground of understanding among different individuals, yet it has gained little acceptance by those who have a distrust of statistical methods. A blend of the two methods represents a realistic compromise that would allow the marine industry and the government to combine their efforts and achieve a mutually beneficial set of objectives in the not so distant future.

The technology of risk-based approaches as they

apply to safety determinations is complex. This complexity has led to these approaches being viewed as unacceptable by many of the current stakeholders in the marine safety process. As a matter of fact the lack of acceptance of risk analysis is frequently attributed to the inherently poor communication of risk within our current safety determination methods.

It is up to the industry to make risk-based standards work. They can do this by taking the initiative to make alternative compliance based on risk assessments acceptable to the U.S. Coast Guard. This can be achieved by working with the U.S. Coast Guard and assisting them to recognize outdated and ineffective standards and regulations. Risk-based standards would then be jointly developed to either supercede or eliminate the existing standards that have been deemed obsolete.

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Towards A Generic Product-Oriented Work Breakdown Structure For Shipbuilding

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ABSTRACT

U.S. Navy ship acquisitions are currently managed using the Ship Work Breakdown Structure, or SWBS, which decomposes ships by separating out their operational systems. This was effective in an era when the entire ship procurement program was physically accomplished using a ship system orientation. However, this is no longer the case and the right type of design and management information is not being collected and analyzed under SWBS.

This paper reports the results of a cooperative effort on the part of shipyards, academia, and the Navy to develop a generic product-oriented work breakdown structure. This new work breakdown structure is a cross-shipyard hierarchical representation of work associated with the design and production of a ship using today's industry practice. It is designed to (a) support design for production trade-offs and investigation of alternative design and production scenarios at the early stages of ship acquisition, (b) supply a framework for improved cost and schedule modeling, (c) translate into and out of existing shipbuilding work breakdown structures, (d) incorporate system specifiers within its overall product-oriented environment, (e) improve data transfer among design, production planning, cost estimating, procurement, and production personnel using a common framework and description of both the material and labor content of a ship project, and (f) provide a structure for 3-D product modeling data organization.

NOMENCLATURE

BOM	Bill of Materials
BUCCS	Boeing Uniform Classification and Coding System
ERAM	Engine Room Arrangement Modeling
GBS	Generic Build Strategy
GPWBS	Generic Product-Oriented Work Breakdown Structure
IPC	Interim Product Catalog
IHI	Ishikawajima-Harima Heavy Industries
NSRP	National Shipbuilding Research Program
PODAC	Production-Oriented Design and Construction
PWBS	Product Work Breakdown Structure
SWBS	Ship Work Breakdown Structure
UMTRI	University of Michigan Transportation Research Institute
WBS	Work Breakdown Structure

BACKGROUND AND PROBLEM STATEMENT

During the past three decades, the shipbuilding industry has changed its production focus from shipboard systems to products and processes. The systems used to collect and manage product and process information in the U.S.-based shipyards have not evolved at the same pace, consequently American shipbuilders have not realized the potential of product orientation to the degree that their Asian and European colleagues have. As technology advanced, the tendency has been to layer new processes on top of the old instead of rebuilding the basic infrastructure. This is suggested by Table I.

The result is that multiple work breakdown structures (WBSs) are used in current U.S. shipbuilding projects. These include shipyard WBSs, supplier WBSs, and the Navy Ship Work Breakdown Structure (SWBS).

Business function	Mid-1960s	Mid-1990s
Ship specification	System	System
Ship design	System	Varies with zone, system, other
Cost estimation	System	Varies
Budgeting	System	Product and process
Planning	System	Product and process
Operations	System / trade	Varies with trade, area, skill

Table I. Evolving design/build orientation.

Problems With SWBS

SWBS is based on shipboard functional systems. "All classification groups in SWBS have been defined by basic function. The functional segments of a ship, as represented by a ship's structure, systems, machinery, armament, outfitting, etc., are classified using a system

of numeric groupings consisting of three numeric digits" [1]. Later, the number of digits was increased to five in an "expanded" form of SWBS [2]. SWBS was intended to be "... a single indenturing language which can be used throughout the entire ship life cycle, from early design cost studies and weight analyses, through production and logistic support development, to operational phases, including maintenance, alteration and modernization" [2]. To a large extent, this goal has been realized.

Today, use of this functional systems architecture from initial concept studies to scrapping causes problems because an information disconnect happens during production. SWBS, being a system-based structure, fails to reflect today's shipbuilding practice. Modern shipbuilding is based on group technology and process analysis, which depend on identification of part and interim product attributes. Interim product information, however, is not available when data is classified exclusively by functional system.

At the early design stages, certain types of major cost drivers such as labor are not easily estimated when SWBS is used because SWBS data does not show the product and process attributes upon which labor expenditure depends. As shipyard technology evolves, capital improvements are made, and processes are improved, SWBS allows no adjustment to reflect increases in efficiency.

LITERATURE REVIEW

Design of Work Breakdown Structures

Product-oriented work breakdown structures are not a shipbuilding industry innovation. Slemaker [3], for example, describes general concepts of work breakdown structure development in civil and defense industries and observes that:

"In all but the simplest, most repetitive cases there is a need to define in detail the work that individual organizations are expected to perform. This work breakdown structure (WBS) should be a product-oriented (as opposed to functional) breakdown of the item being developed or produced or the service provided."

According to reference [4], "A work breakdown structure (WBS) is a product-oriented family tree composed of hardware, software, services, data and facilities which results from systems engineering efforts during the acquisition of a defense materiel item. A work breakdown structure displays and defines the product(s) to be developed and-or produced and relates the elements of work to be accomplished to each other and to the end product(s). "

During the 1980's the National Shipbuilding Research Program (NSRP) published classic reports [5], [6], [7] which documented the progress in product work breakdown structure (PWBS) development and implementation that had been made by Ishikawajima-Harima Heavy Industries (IHI) in Japan in the 1970's. Also published by the NSRP was a report [8] which presented the results of a PWBS development project and contained a re-publication of a Boeing Commercial Airplane Company internal report [9] describing a 1970's-era conception of a complete PWBS/group technology implementation. This system was called the Boeing Uniform Classification and Coding System, or BUCCS.

Boeing's product classification efforts in the 1970's had two stated goals: minimization of parts re-design via family-oriented design retrieval, and grouped production based on family identification [9]. The design retrieval goal was attacked first, then production considerations were built in. Boeing's approach was to classify products, means of production, and controls over production.

The late 1970's IHI approach to developing a product-oriented work breakdown structure as documented by Okayama and Chirillo [5], [6] shares with the Boeing BUCCS system a strong orientation towards part and sub-assembly description, but in addition it explicitly relates those processes to ship final assembly. A three-dimensional PWBS is laid out, with three axes of information:

1st axis: Type of work (fabrication or assembly; hull, outfit, or paint.)
2nd axis: Product resources (material, manpower, facilities, expenses)
3rd axis: Product aspects. (system, zone, problem area, stage.)

The third dimension in this method is closely linked to the product-oriented ship design cycle of basic design (total system), functional design (system), transition design (system, zone) and detail design/working drawings (zone, problem area, stage). The zone consideration adds a specific ship geography parameter.

Use of Work Breakdown Structures

Standard textbooks on production and operations management describe the use of work breakdown structures. Chase and Aquilano [10], for example, introduce WBSs as a tool to organize projects or programs through the decomposition of the statement of work into tasks, sub-tasks, work packages and activities. They observe that:

"The work breakdown structure is the heart of project management. This subdivision of the objective into smaller and smaller pieces clearly defines the system and contributes to its understanding and success. Conventional use shows the work breakdown structure decreasing in size from the top to bottom and shows this level by indentation to the right:

Level	
1	Program
2	Project
3	Task
4	Sub-task
5	Work Package."

Chase and Aquilano [10] go on to explain that this WBS indenture is imposed upon and controlled through the bill of materials (BOM) file:

"The BOM file is often called the *product structure file* or *product tree* because it shows how a product is put together. It contains the information to identify each item and the quantity used per unit of the item of which it is a part."

PROJECT FORMULATION

The goal of the project was to develop a generic product-

oriented work breakdown structure (GPWBS) applicable to a merchant-type ship project for which the building yard had not yet been selected. The "generic" aspect is in the applicability of the structure to various shipyards. Specific goals for the GPWBS were that it:

- Support design for production trade-offs and investigation of alternative design and production scenarios at the early stages of ship design.
- Supply a framework for improved Navy cost modeling based on the way that ships are built.
- Translate into and out of other, existing shipyard work breakdown structures.
- Incorporate system specifiers within its overall product-oriented environment.
- Improve data transfer among design, cost estimating, procurement, and production personnel using a common framework and description of both the material and labor content of a ship project.
- Provide a structure for 3-D product modeling data organization.

The development of the GPWBS was carried out by a team of naval architects, engineers, estimators, and planners from several major U.S. shipyards, the Shipbuilding Technologies Department at David Taylor Model Basin, the University of Michigan Transportation Research Institute, and Designers and Planners, Inc. Information and feedback was provided by a large European shipyard.

GPWBS ATTRIBUTES AND STRUCTURE

In order to meet the project goals, the following structural attributes were required of the GPWBS:

- Three basic types of information content -- product structure, stage or process, and work type.
- A clean product structure, devoid of process or organization information.
- Expression of the stages used in the full build cycle and the shipbuilding processes defined within each stage.
- Work type identification, with the work types characterizing product aspects in terms of organization, skill, and scope of work for interim products.
- Data from all participating shipyards must fit into the GPWBS.

The resultant is a hierarchical representation of work associated with the design and building of a ship based on product structure, classification and coding. The product structure is represented by connecting interim products, the classification is the organization of work type and stage (process) and the coding provides the name and address associated with the interim product.

Product structure

The GPWBS product structure has eight levels and is arranged to connect the interim products. The product structure is a hierarchical framework that identifies interim products and their related components and parts. Figure 1 represents the product classification by level within the product structure.

Of particular importance to this product structure is that it is product oriented only, with no organizational or process content.

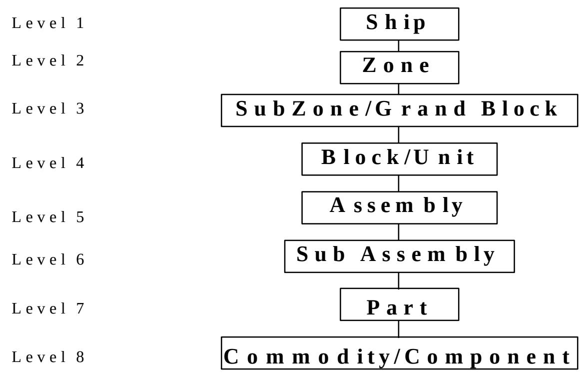


Figure 1. Product Structure.

Stages

Stages are the sequential divisions of the shipbuilding process. The GPWBS has adopted a broad view of shipbuilding stages by including the complete cycle from ship design to post delivery. They are sorted into construction and non-construction stages. Table II shows typical shipbuilding stages.

Non-construction	Construction
Design	Fabrication
Planning	Sub-assembling
Procurement	Assembling
Material management	On-unit installation
Launching	On-block installation
Testing	On-grand block installation
Delivery	Erection
Post-delivery	On-board installation

Table II. Shipbuilding stages.

Non-construction stages cover portions of the shipbuilding cycle that involve the design, planning, material definition, programmatic aspects, support, and other services of a ship project. Construction stages refer to the physical realization of a ship. In both the non-construction and construction stages, process is the key element. Stages can be divided into lower levels of processes depending upon the level of process management the shipyard uses to control its operations.

In the non-construction stages, design is defined as the preparation of engineering, material definition and documentation for construction and testing. The work description, sequencing, scheduling and resource allocation to build a product is the planning stage. The procurement stage is the requisitioning, ordering and expediting of materials. Material management is the receiving, warehousing and distribution of material. Other non-construction stages that are closely aligned to the construction stages are launching, testing, delivery, and post-delivery activities.

The construction stages address the sequence and specific processes to manufacture the ship. These stages are fabrication, sub-assembly, assembly, on-unit installation, on-block installation, grand-block installation, erection, and on-board installation.

Work Types

The third element of the GPWBS is the work type. Work type classifies the work by skill, facility and tooling requirements, special conditions and/or organizational entities. The work type is

used to attach a scope or pallet of work to an interim product at a specified stage of shipbuilding. As an example, for a block interim product at the design stage with the work type "engineering," the scope of work is to produce the drawing of the block. Table III shows work types.

Non-construction	Construction
Administration	Electrical
Engineering	Hull outfit
Material handling	HVAC
Materials	Joiner
Operations Control	Machinery
Production Service	Paint
Quality assurance	Pipe
Testing/Trials	Structure
	Unit construction

Table III. Work types.

Application of work type to the GPWBS permits identification of all work whether the work is considered a direct or an indirect charge to a project. For each interim product, each work type has specific work type(s) attached to it at each stage.

Application of the Structure

The three elements (product structure, stage and work type) form the GPWBS as shown in Figure 2. These GPWBS dimensions represent different kinds of data -- the product structure is a hierarchy, stages are sequential and work types represent categories. A Cartesian space is not implied. However, a graphic representation using three axes has been found to be a useful device for introducing the GPWBS system at shipyards and in a university classroom.

As an example of a GPWBS system application, Figure 3 shows a “block” interim product at the “on block outfit” stage for the “pipe” work type. The intersection of the three coordinates can be pictured as the scope of work in piping.

An interim product over multiple stages for a single work type can also be identified. In Figure 4, the work type “pipe” through stages of “fabrication,” “sub-assembly” and “on block outfitting” is shown for a “block” interim product.

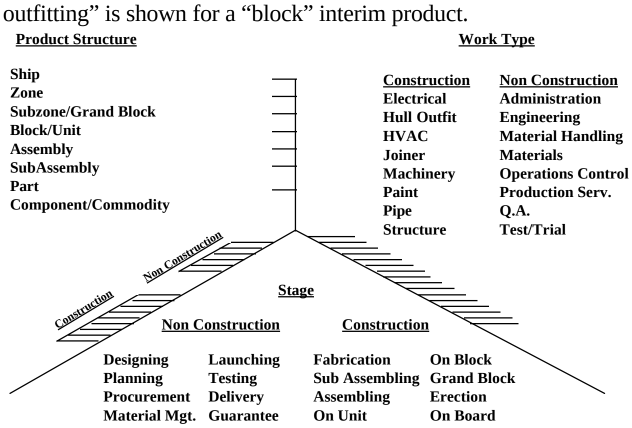


Figure 2. GPWBS system.

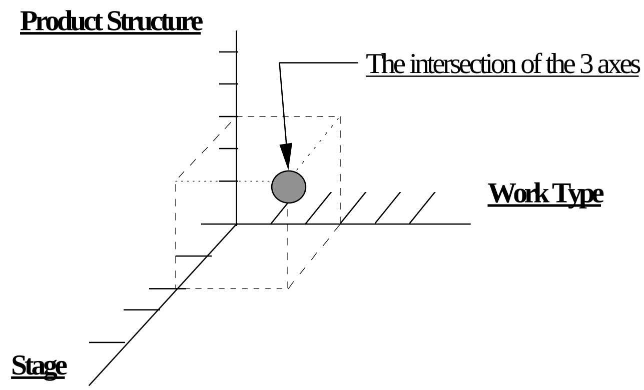


Figure 3. GPWBS interim product example.

A “unit” interim product at the “on unit outfit” stage, collecting multiple work types (“pipe,” “electrical,” and “machinery”) is shown in Figure 5. Figure 6 demonstrates that the interim product over multiple stages and multiple work types can be identified. Figure 7 indicates how multiple interim products are represented by defining the scope of work for multiple work types over multiple stages.

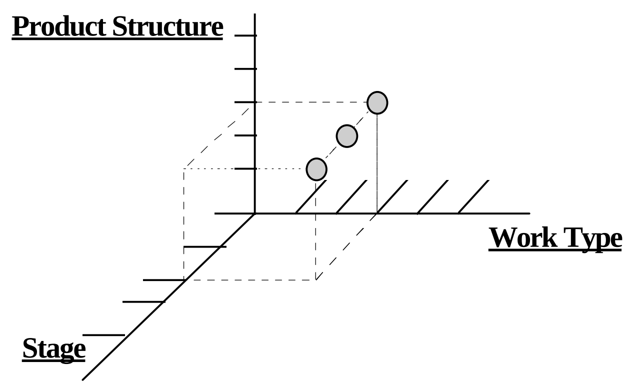


Figure 4. Interim product for multiple stages and a single work type.

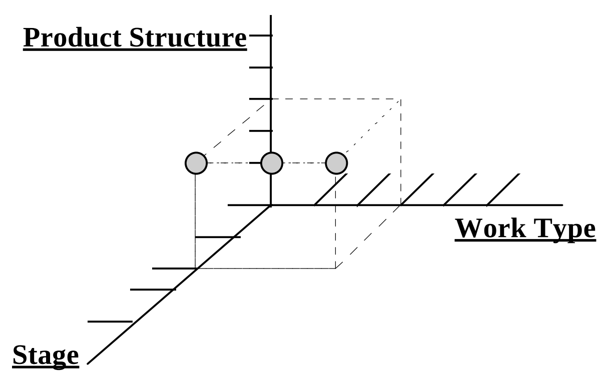


Figure 5. Interim product for a single stage and multiple work types.

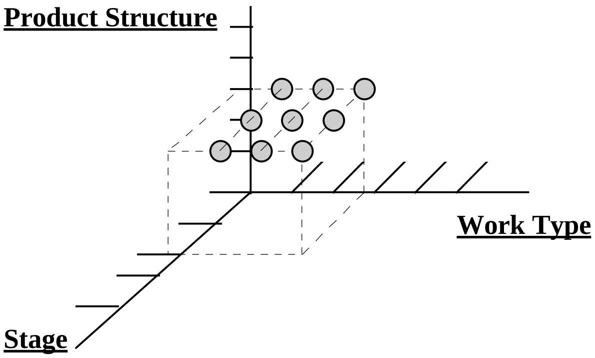


Figure 6. Interim product for multiple stages and multiple work types.

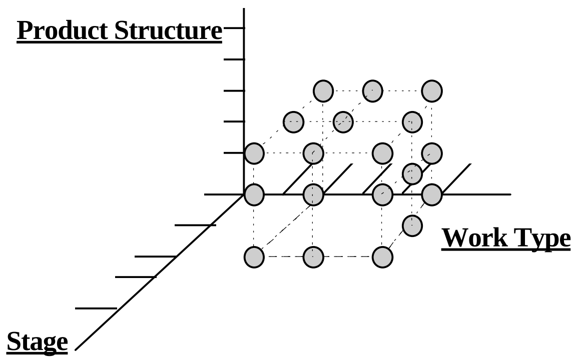


Figure 7. Multiple interim products with multiple stages and work types.

Two significant uses of data and cost measurement are actively used by shipyards. While the three elements of the GPWBS organize the bill of material (BOM) data such that the intersection describes work associated with an interim product, the shipyards further divide cost measurement into product and process controls.

Figure 8 introduces an aspect of control that focuses on process measurement without reference to the product cost. The process measurement is more focused on the lower tiers of the product structure, while product measurement is used in the higher tiers of the product structure. The point of demarcation varies between shipyards, generally a result of the level of automation applied in their build plans. The more automated or volume driven the shipyards' factories are run the higher the level of process measurement usually applied.

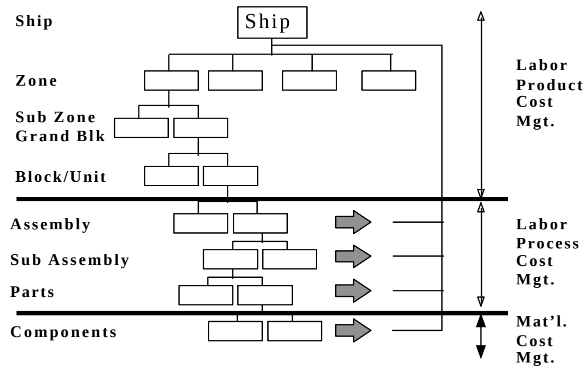


Figure 8. Product and process logic.

CODING

A useful coding system for the GPWBS must be capable of handling the three axes of the GPWBS structure. In addition, it must include coding fields for interim products and incorporate the following data elements:

- Sub-stages
- Ship type
- Drawings
- Process
- Schedule
- Unit of measure
- Quantity
- Labor hours
- Material catalog
- System
- Find number (number on drawing for each interim product.)
- Location.

Available Methods

Classification and coding systems generally fall into one of three categories.

- Monocode is hierarchical and is based on a tree structure where the digits at one level determine the subsequent digits at lower levels in the tree.
- Polycode (or chain code) is a non-hierarchical code which has a chain relationship seen through a matrix formation.
- Hybrid code (or mixed code) combines elements of the mono and poly coding structures.

Each type can use numerical, alpha or alpha/numerical characters in information fields. In the past, computer capacity limited both the available field lengths and the use of alpha or alpha-numeric codes. This is no longer a practical constraint. However, for this project, existing shipyard limits or practices must be accommodated.

The monocode tree structure is organized such that the fields of information are strung together to provide very specific addresses for each coded element within the PWBS. Therefore, the lowest level element, "part," is uniquely coded to the highest level element in the tree, "zone." Figures 9 and 10 demonstrate the monocode applications using both numerical and

alpha/numeric fields.

When a polycode system is used a chain of digits is defined in the fields of information. One reason to use polycodes is that it reduces the number of digits to name the fields of information. However, reference tables are required as the code does not provide a transparent, "Dewey decimal"-style address to each element within the structure as monocodes do. Table IV is an example of a polycode system. Without a reference table the user is unable to associate a lower level interim product with the higher level interim product to which it belongs.

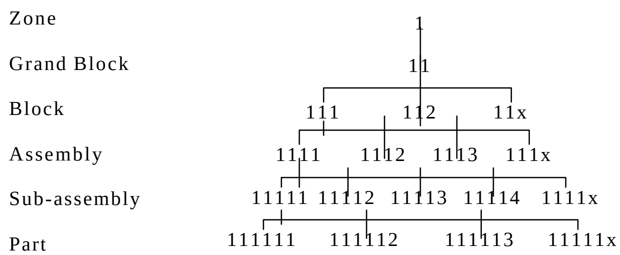


Figure 9. Numerical monocode.

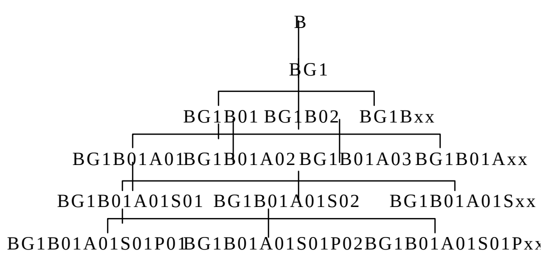


Figure 10. Alpha-numeric monocode.

Interim Product	Code
Zone	B
Grand Block	G011
Block	B023
Assembly	A041
Subassembly	S023
Part	P079

Table IV. Polycode application.

Hybrid coding is used when a mixture of associative and non-associative information is acceptable. For example, the higher levels of a product structure may require hierarchical associativity while the lower interim products may only require sequentially coded fields to attach to the higher interim products or parent relationship.

CODING APPROACH

The following approach has been adopted in the GPWBS coding system.

- Separate fields are used to identify product structure, stage and work type.
- A monocode (hierarchical) system is used in the product structure field, with polycodes in the other two fields.
- Alpha-numeric code is used in the product structure field while Roman letters are used in the stage and work type fields.

Table V lays out the fields of information to be coded. In this figure, the third row identifies the product structure titles, the fourth row identifies the product structure levels, and the fifth row corresponds to the descriptions in the work section.

Code

The code for the GPWBS is as follows, working through Table V from column 1 to column 15:

<u>Product Structure:</u>

1. *Ship* code is a numeric code in sequence with the shipyards' numbering scheme.

2. *Zone* is the second level of the product structure. The zones are:

Bow	B
Stern	S
Machinery	M
Cargo	C
Deckhouse	D
Ship-wide	W

3. *S/O ind.* is the structure vs. outfit indicator coded as:

Structure	S
Outfit	Z

This indicator, as mentioned before, is required to avoid any duplication in the coding between the structural interim products and outfit interim products.

4. *I/P ind.* is the interim product indicator. The code is:

Sub-zone	Z
Grand block	G
Block	B
Unit	U
Assembly	A
Sub-assembly	S
Part	P
Commodity/Component	C

5. *Location* is the identifier for position on the ship. Longitudinal beginning with 01 denotes the number within each zone from forward to aft, Vertical beginning with 01 denotes the number within each zone from bottom to top, and Transverse locations within each zone are numbered with centerlines as zero, starboard odd and port even.

6. *Assy.* is the assembly interim product. Assemblies are numbered sequentially within each block, unit or sub-zone.

7. *S/A* is the sub-assembly interim product. Sub-assemblies are numbered sequentially within each assembly. A sub-assembly can go directly to a block, unit or sub-zone.

8. *Part* is the lowest manufactured level of the structure. Parts are numbered sequentially within a sub-assembly or other interim product.

9. *Mat. id.* is the material identifier for commodity and component. This column is also used to indicate system when system is the identifier. The code is:

- Commodity MYYXX
- Component CYYXX
- System SAAAB

Most shipyards have existing commodity (raw material) codes and may even have a standard part numbering system for components (purchased equipment). It should be possible for them to use their existing codes here.

10. Column 10 classifies the interim product types by *ship types*. For example, geared bulk carrier or post-Panamax containership might be specified.

11. *Interim Product Type* identified in column 11 is the classification of interim products within the

Prod Struc	Product Structure															Stage	Work Type
					Location							Ship type	I/ P Type	Attr 1	Attr 2		
	Ship	Zone	S,/O ind.	I/P ind.	long.	vert.	trans	Assy	S/A	Part	Mat. id.						
	L-1	L-2	L-3 & L-4					L-5	L-6	L-7	L-8						
	1	2	3	4	5			6	7	8	9	10	11	12	13	14	15

Table V. Fields of data by product structure, stage and work type.

Prod Struc	Product Structure															Stage	Work Type
					Location							Ship type	I/ P Type	Attr 1	Attr 2		
	Ship	Zone	S,/O ind.	I/P ind.	long.	vert.	trans	Assy	S/A	Part	Mat. id.						
	L-1	L-2	L-3 & L-4					L-5	L-6	L-7	L-8						
	1	2	3	4	5			6	7	8	9	10	11	12	13	14	15
	7408	B	S	P	01	01	0	02	13	13	S11	HBC	1	1	0	FB	ST
	7408	B	Z	S	01	05	1	03	21	00	S24	HBC	3	1	0	SA	PI

Table VI. Coding examples.

Prod Struc	Product Structure															Stage	Work Type
					Location							Ship type	I/ P Type	Attr 1	Attr 2		
	Ship	Zone	S,/O ind.	I/P ind.	long.	vert.	trans	Assy	S/A	Part	Mat. id.						
	L-1	L-2	L-3 & L-4					L-5	L-6	L-7	L-8	L-1	L-3 - L-7				
Grand Block	7408	**B**	**S**	**G**	**01**	**01**	**0**	**00**	**00**	**00**	**S 1000**	**HBC**	**1**	**1**	**4**	**GB**	**ST**
Block	7408	**B**	**S**	**B**	**01**	**01**	**0**	**00**	**00**	**00**	**S 1000**	**HBC**	**1**	**2**	**2**	**AS**	**ST**
Assy	7408	**B**	**S**	**A**	**01**	**01**	**0**	**12**	**00**	**00**	**S 1000**	**HBC**	**1**	**1**	**2**	**AS**	**ST**
S/A	7408	**B**	**S**	**S**	**01**	**01**	**0**	**12**	**09**	**00**	**S 1000**	**HBC**	**1**	**2**	**0**	**SA**	**ST**
Part	7408	**B**	**S**	**P**	**01**	**01**	**0**	**12**	**09**	**71**	**S 1000**	**HBC**	**1**	**7**	**1**	**FB**	**ST**
Comm	7408	**B**	**S**	**C**	**01**	**01**	**0**	**00**	**00**	**00**	**MHP13**	**HBC**					
S/Z	7408	**B**	**Z**	**Z**	**01**	**05**	**1**	**00**	**00**	**00**	**0000**	**HBC**	**4**	**0**	**0**	**OO**	**HV**
Unit	7408	**B**	**Z**	**U**	**01**	**05**	**1**	**00**	**00**	**00**	**S 5140**	**HBC**	**7**	**5**	**0**	**OU**	**UC**
Assy	7408	**B**	**Z**	**A**	**01**	**05**	**1**	**17**	**00**	**00**	**S 5140**	**HBC**	**4**	**7**	**3**	**AS**	**HV**
S/A	7408	**B**	**Z**	**S**	**01**	**05**	**1**	**17**	**21**	**00**	**S 5140**	**HBC**	**4**	**1**	**1**	**SA**	**HV**
Part	7408	**B**	**Z**	**P**	**01**	**05**	**1**	**17**	**21**	**11**	**S 5140**	**HBC**	**4**	**1**	**4**	**FB**	**HV**
Comp	7408	**B**	**Z**	**C**	**01**	**05**	**1**	**17**	**21**	**11**	**MH0 12**	**HBC**					

Table VII. Examples of code for all levels of the product structure interim products.

Z	Sub-Zone		2	Machinery	
CODE	**PROPULSION MACHINERY**	**SHAFTING**	**PROPULSOR (S)**	**AUXILIARY MACHINERY**	**MACHINERY CONTROLS**
0	NOT USED	NOT USED	NOT USED	NOT USED	NOT USED
1	SLOW SPEED DIESEL	SOLID SHAFT	SINGLE PROPELLER	DIESEL GENERATORS	PNEUMATIC
2	GEARED MEDIUM SPEED DIESEL	SOLID MUFF COUPLED SHAFT	TWIN PROPELLER	STEAM GENERATORS	HYDRAULIC
3	GEARED HIGH SPEED DIESEL	HOLLOW FLANGED SHAFT	SINGLE WATERJET	EXHAUST GAS BOILER	ELECTRIC/ ELECTRONIC
4	DIESEL ELECTRIC	HOLLOW MUFF COUPLED SHAFT	TWIN WATERJET	OIL FIRED BOILER	
5	STEAM TURBINE			DISTILLER	

Table VIII. Machinery interim product attribute #1.

product structure levels. The interim product type subdivides the product structure by group technology and other major categories.

12 and 13. The last two columns of the product structure field are used to set up interim product attributes.

14. *Stages* are the sequential shipbuilding processes coded as two alphabetic digits as follows:

Non-Construction Stages

Design	DS
Planning	PL
Purchasing	PR
Material management	MM
Launch	LA
Testing	TE
Delivery	DL
Post-delivery	PD

Construction Stages

Fabrication	FB
Sub-assembly	SA
Assembly	AS
On-unit installation	OU
On-block installation	OB
On-grand block installation	GB
Erection	ER
On-board installation	OO

15. *Work Types* are classed by skill, facility and tooling, special conditions and organizational entities. The code for the work type is alphabetic as follows:

Non-Construction Work Type

Administration	AD
Engineering	EG
Material handling	MH
Materials	MA
Operations control	OC
Production services	PS
Quality assurance	QA
Test & trials	TT

Construction Work Type

Electrical	EL
Hull outfit	HO
HVAC	HV
Joiner	JN
Machinery	MC
Paint	PA
Pipe	PI
Structure	ST
Unit construction	UC

Table VI gives two examples of how the system is applied. The first example belongs to a ship 7408, bow zone, structural part, located in the forward most part of the bow lowest level and on centerline. The stage is fabrication and the work type is structure.

The second example is a pipe piece. It belongs to ship 7408, bow zone, outfit, sub-assembly interim product, located in the forward most part of the bow at the fifth level up from the bottom and on the starboard side. The stage is sub-assembling and the work type is pipe.

These two examples indicate how to build a coded number for an interim product at a certain stage and designated to a specific work type assignment. Other attributes can be added as required or customized to suit individual practice. As an example the unit of measure and labor hours would be covered in an interim product catalog (IPC).. This effort is under way as described in the Conclusions and Recommendations sections below.

Table VII shows the application of the coding system to all levels of the product structure. Columns 10 through 13 in Tables V through VII are further detailed in Tables VIII through XIII, which show some of the other attributes that can be applied to an interim product.

CODE	DESCRIPTION
0	NOT USED
MTVL	Merchant - Tanker, VLCC
MLNG	Merchant - Liquified natural gas carrier
MBGL	Merchant - Bulk carrier, geared, large
MOBO	Merchant - Oil/bulk/ore carrier
MCPM	Merchant - Containership, Panamax
MROR	Merchant - Ro-ro
NLSD	Naval - Landing ship dock
NDDG	Naval - Guided missile destroyer
TAKR	Sealift - Vehicle cargo ship
	. . . etc . . .

Table IX. Sample ship type codes.

CODE	DESCRIPTION
0	NOT USED
1	STRUCTURE
2	MACHINERY
3	PIPING
4	HVAC
5	ELECTRICAL
7	UNIT
8	

Table X. Interim product type code.

Z	Sub-Zone	3	Piping
CODE		TYPE	
0		NOT USED	NOT USED
1		STRAIGHT PIPE	
2		BENT PIPE	
3		PIPE FITTING	
4		VALVES	
5		PUMPS	
6			

Table XI. Pipe interim product attributes #1 & 2.

Z	Sub-Zone	4	HVAC
CODE		TYPE	GEOMETRY
0		NOT USED	NOT USED
1		STRAIGHT DUCT	CONSTANT SECTION
2		DUCT SINGLE 90 RADIUS	REDUCING SECTION
3		DUCT SINGLE <90 RADIUS	
4		DUCT FLANGES	

5	DUCT HANGERS	
6	DUCT INSULATION	
7	FANS	
8	INLETS	
9	TERMINALS	

Table XII. HVAC interim product attributes #1 & 2.

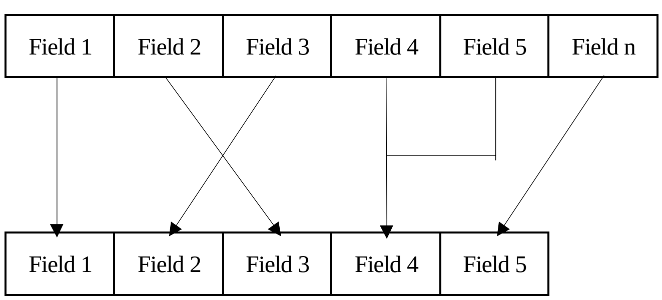
B	Block	1	Structure
CODE	**TYPE**		**GEOMETRY**
0	NOT USED		NOT USED
1	SINGLE BOTTOM		3D PLANE
2	DOUBLE BOTTOM		3D CURVED
3	SINGLE SIDE		2D PLANE
4	DOUBLE SIDE		2D CURVED
5	DECK		
6	TRANSVERSE BULKHEAD		
7	LONGITUDINAL BULKHEAD		
8	FLAT		
9	MAJOR FOUNDATION		

Table XIII. Structure interim product attributes #1&2.

MAPPING TEST

Mapping is the process of converting data from one work breakdown structure to another. There are two steps in the mapping process. The first is to establish a relationship between the fields of the two WBSs so that data records in the first format can be converted to the second. This is shown in Figure 12. Having aligned the fields, the transfer of cost data or other information (for example, bill of materials data) can then be accomplished. The complete procedure is laid out in a series of examples below.

Shipyard PWBS Data Record *



Generic PWBS Data Record

* Data records include information from Work Orders (labor data) and from Purchase Orders (material data).

Figure 12. WBS mapping: alignment of fields.

Mapping "Shipyard A" Work Breakdown Structure To The GPWBS

To demonstrate the process, a shipyard-specific map similar to the general one shown in Figure 12 was constructed for aligning the product-oriented WBS of an actual shipyard, "Shipyard A," with the GPWBS.

The product-oriented work breakdown structure for Shipyard A is used in their work order records (used to track labor data) and purchase orders (used to track material data). Because the nature of the information in work orders is different from that in purchase orders, the data fields in these two records are different. Table XIV shows the format of Shipyard A's work order and purchase order records, which were derived from the shipyard's product-oriented WBS. The remainder of this section of the paper will focus on mapping shipyard A's product-oriented WBS to the GPWBS.

Table XV shows the GPWBS record structure, to which the fields in Shipyard A's product-oriented WBS from the previous page must be mapped. This record structure is fully described in the Coding section and is not repeated here except in summary form, and as it relates to each specific example. The fields in these records are shown and explained in successive steps to show the overall map in its entirety.

Table XVI shows how shipyard A's job number, the first field in their work order and in their purchase order, implicitly includes shipyard A's hull number.

Shipyard "A" Work Order Record	
Job Number	
Group Number	
Sub-group Number	
Item Number	
Block/Unit Number	
Zone Number	
Weight	
Description	
Quantity	
Unit of Measure	
Estimated Hours	
Planned Start Date	
Actual Hours	
Actual Start Date	
Actual Completion Date	
Product Type (Work Type)	

Shipyard "A" Purchase Order Record	
Job Number	
Group Number	
Sub-group Number	
Item Number	
Weight	
Description	
SWBS Reference	
Quantity	
Unit of Measure	
Total Cost	
Date Ordered	
Expected Receipt Date	
Actual Receipt Date	

Table XIV. Work order and purchase order format, shipyard A.

Shipyard A does not explicitly assign a ship type. Since the generic product-oriented WBS explicitly includes ship type, the table shows how the shipyard's job number and hull number would be used to assign the ship type in the generic product-oriented WBS.

Table XVII shows how shipyard A's zone designators relate to the generic product-oriented WBS zone designators. The descriptions in these zone designator tables relate specifically to commercial vessels. Other ship types will likely have different zone descriptions.

Table XVIII shows typical relationships between shipyard "A" block number/locating scheme and the generic PWBS. As explained in the previous section, blocks represent structural elements only. Non-structural elements are discussed later.

Note that all blocks in these examples are in the shipyard's zone 4. Therefore, the corresponding generic product-oriented WBS zone designator is D, as shown in Table XVII. All shipyard block numbers for zone 4 are three digit numbers beginning with 4.

The shipyard's transverse location and deck level fields correspond directly to the generic product-oriented WBS transverse and vertical location fields.

Generic Product-Oriented WBS Data Record	
Ship Type	
Hull Number	
Product Structure:	
Zone	
Structure/Outfit/Material Indicator	
Interim Product Indicator	
Longitudinal Location	
Vertical Location	
Transverse Location	
Assembly	
Sub-Assembly	
Part	
Commodity/Component	
Interim Product Type	
Interim Product Attribute 1	
Interim Product Attribute 2	

Interim Product Attribute n	
Stage of Shipbuilding:	
Non-construction Stage	
Construction Stage	
Work Type:	

Table XV. GPWBS data record format.

While this shipyard uses P for port, S for starboard, and C for centerline, the generic product oriented WBS uses the standard Navy system of "even number to port, odd to starboard" with "0" denoting a centerline location. Associating the shipyard's frame number directly to the generic product-oriented WBS longitudinal locator is not quite as straightforward.

Shipyard Job Number	Shipyard Hull Number	**Generic** Product-Oriented **WBS Ship Type Code**
C8-275G	2367	TAO
C8-230C	2371	LSD
C3-300	2379	LSD
C3-075B	002	MHC
C3-075C	003	MHC
C3-075D	004	MHC
C3-0140	2372	WAGB
C3-222A	2373	TAKR
C3-222B	2374	TAKR
C3-222C	2375	TAKR
C3-222D	2376	TAKR

Table XVI. Sample lookup table showing shipyard A job number & hull number relation to GPWBS ship type.

Shipyard A Zone Designator	Shipyard A Zone Description	**Generic** Product-Oriented **WBS Zone Designator**
1	Stern	S
2	Cargo (Ballast, Fuel)	C
3	Cargo (Ballast, Fuel)	C
4	Deckhouse	D
5	Cargo	C
6	Cargo	C
7	Bow	B
8	Cargo	C
9	Machinery	M
		W*

* W = ship-wide zone, used only in Generic PWBS

Table XVII. Zone designator relationships, shipyard A to generic product-oriented WBS.

The generic product-oriented WBS longitudinal locator, as explained in the previous section, shows the forward-most block(s) in each zone at a given vertical to be 01, and the block(s) immediately aft of these to be 02. The longitudinal locator continues to increment proceeding aft until reaching the zone's aft boundary. It is reset to 01 for each vertical level addressed, and for each zone.

The generic product-oriented WBS side of the table can be seen to include two fields not explicitly addressed by this particular shipyard, namely the Structure/Outfit/Material Indicator and Interim Product Indicator. These are fully explained in the previous section. For the cited examples, the shipyard's block number represents only the structural elements within the region containing that block, while the outfit elements are shown by this shipyard in terms of sub-zones. Examples of sub-zones are presented later. In the simplest case, a block contains all the structural elements in a given region, and a sub-zone contains all other elements in that same region. However, block and sub-zone boundaries need not be identical.

Since Table XVIII shows only blocks (i.e., structure), note that the corresponding S/O/M Indicators in the generic product-oriented WBS are all shown as "S" entries. Similarly, all Interim Product Indicators in the generic PWBS are all shown a "B" entries, for Block. Table XIX shows similar typical relationships between the shipyard sub-zone numbering/locating scheme and the generic product-oriented WBS. As explained in the previous section, sub-zones represent outfit elements only.

Shipyard A Structural Blocks					Generic PWBS Structural Blocks					
Zone	Block No.	Transv. Loc.	Fr.	Dk.	Zone	S/O/M Indicator	I/P Ind.	Longl. Loc.	Vert. Loc.	Transv. Loc.
4	420	P	85	02	D	S	B	01	02	2
4	421	S	85	02	D	S	B	01	02	1
4	422	P	90	02	D	S	B	02	02	2
4	423	S	90	02	D	S	B	02	02	1
4	424	P	95	02	D	S	B	03	02	2
4	425	S	95	02	D	S	B	03	02	1
4	426	C	100	02	D	S	B	04	02	0
4	427	C	100	02	D	S	B	04	02	0

Table XVIII. Shipyard A structural block relation to GPWBS.

All sub-zones in these examples are in the shipyard's zone 4. Therefore, the corresponding generic product-oriented WBS

Zone Designator is D, as shown in Table XVII. All shipyard sub-zone numbers are defined by the sub-zones' vertical, longitudinal, and transverse locations. Associating the shipyard's location scheme for outfit sub-zones with that for generic product-oriented WBS is the same as for the structural blocks discussed above.

Again, the generic product-oriented WBS side of the table shows the Structural/Outfit/Material Indicator and the Interim Product Indicator. For the cited examples, the shipyard's sub-zone number represents only the outfit elements within the region containing that sub-zone. Since Table XIX shows only sub-zones (i.e., outfit), note that the corresponding S/O/M Indicators in the generic product-oriented WBS are all shown as "Z" entries, with Z representing outfit. Similarly, all Interim Product Indicators in the generic product-oriented WBS are all shown as "Z" entries.

Table XX shows how Shipyard A's group numbers relate to the work types defined in the GPWBS. The codes shown for the GPWBS work types were explained in the previous section so they are not repeated here. Table XXI shows the shipyard's material cost group codes and descriptions, and their associated Ship Work Breakdown Structure (SWBS) numbers. This information supports purchase order record mapping examples which follow.

Shipyard A Outfit Sub-Zones				Generic Product-Oriented WBS Outfit Sub-Zones					
Zone	Sub-zone Number	Fr.	Dk.	Zone	S/O/M Ind.	I/P Ind.	Longl Loc.	Vert. Loc.	Trans v Loc.
4	01-083-1P	83	01	D	Z	Z	01	01	2
4	01-083-1S	83	01	D	Z	Z	01	01	1
4	01-091-1P	91	01	D	Z	Z	02	01	2
4	01-091-1C	91	01	D	Z	Z	02	01	0
4	01-091-1S	91	01	D	Z	Z	02	01	1

Table XIX. Shipyard A outfit sub-zone relation to generic product-oriented WBS.

Shipyard A Group Number	Shipyard A Group Description	Generic Product-Oriented WBS Work Type
01	Engineering	EG
02	Hull Steel	ST
03	Superstructure	ST
04	Joiner	JN
06	Piping	PI
07	Machinery	MC
08	Electrical	EL
09	Sheet metal	HO
10	Carpentry	HO
11	Insulation	HO
12	Clean and Paint	PA
13	Construction Services	PS
16	Fittings	HO
17	Outfitting	HO
18	Deck Covering	HO
19	Jigs and Dies	HO
20	Foundations	HO
23	Tests and Trials	TT
25	Mold Loft	PS
26	Launching	PS
27	Production Department	PS
28	Quality Control	QA
31	Warehousing	PS
33	Dry-docking/Shifting	PS
34	Insurance	AD
43	Weld Rods, Steel Freight	MA
45	Spares	MA
46	Machinery Package Units	UC
81	Program Management	AD
82	Estimating	AD
97	Miscellaneous Materials	MA

Table XX. Shipyard A product types versus generic work types.

Shipyard A Material Cost Group Number	Shipyard A Material Cost Group Description	SWBS
02-00	Steel Group	100
02-02	Hull Steel	110
02-06	Structural Hull Piping	
03-00	Superstructure Steel	150
06-00	Piping	505
06-01	Bilge and Ballast System	529
06-02	Cargo System	
06-03	Firemain System	521
06-04	Salt Water Cooling System	524
06-05	Flushing System	521
06-06	Fresh Water Cooling System	532
06-07	Potable Water System	533
06-08	Wash Water System	
06-09	Fuel Oil System	261
06-10	Lube Oil System	262
06-11	Compressed Air System	551
06-12	Steam Systems	517
06-13	Heating System	511
06-14	Fire Extinguishing System	555
06-15	Mud System	
06-16	Refrigeration System	516
06-17	Hydraulic System	556
06-18	Plumbing and Drains	
06-19	Sounding Tubes, Vents	506
06-23	Distilled Water System	531
07-01	Main Propulsion	200
07-02	Generators	310

Table XXI. Shipyard A material cost groups vs. SWBS.

Mapping Labor Data to the GPWBS

Shipyard A labor data is tracked via work orders. Figure 13 shows the yard's work order for installing miscellaneous outfit items in the deckhouse of an LSD (Landing Ship Dock). In this figure, Yard A's Group Number maps to the GPWBS Work Type, Sub-Group Number maps to Stage, and Zone Number is broken into the GPWBS Product fields. Having established the GPWBS code for this work order, the schedule and labor data is then assigned to the GPWBS code and in this way the GPWBS data set is built for this ship.

Figure 14 shows a second outfit item installation work order very similar to the first. Comparing the two records, one can see that the labor man-hours associated with each of these work orders cannot be viewed below the HO (hull outfit) work

type at product structure level 3, deckhouse sub-zone.

Figure 15 shows a pipe welding work order for a system that will eventually be in the machinery zone. The work for this particular activity is performed On-unit and its Work Type is mapped to GPWBS Unit Construction, as shown in Table 20. This work can be viewed at GPWBS product structure level 4, machinery unit, as shown in Figure 1.

Mapping Material Data to Generic PWBS

Figure 16 shows a representative shipyard purchase order. Working through the mapping process will show how it works. The shipyard A group 6 entry corresponds to GPWBS Work Type Piping (PI) as shown in Table XX. The purchase order includes a description of the functional system, Bilge and Ballast System, and its associated Ship Work Breakdown Structure (SWBS) number. This particular purchase order represents a "roll-up" or summation of all purchased elements of the Bilge and Ballast System, the elements including pumps, piping, valves, etc. The GPWBS Zone for this system is shown to be ship-wide (W). All purchase orders would inherently carry an S/O/M Indicator of M for material. This system's Interim Product (I/P) Indicator is shown as "F" for Functional as can be seen in the list of Interim Product Categories in the Coding section (which does not yet include any `F` entries). There are no locators shown (i.e., longitudinal, vertical, and transverse) since the piping run extends throughout the entire length of the ship. Because the system is ship-wide, it is not associated with a GPWBS Assembly, Sub-Assembly, or Part, so each of these fields has a `0` entry. Since this record actually represents a roll-up of purchase orders executed for the entire system, it has a `0` shown in the Component/Commodity field. Material purchases would be considered in the Purchasing (PR) stage and of the Material (MA) Work Type. The SWBS number entry is a direct transfer from the purchase order to the GPWBS. The GPWBS product level chart (Figure 1) indicates that the cost data can be viewed at two levels (at level 8 for the piping when it is bought; level 3 and above for the functional system after it is installed in the ship.

Figure 17 is a purchase order for flanges of a specified piping system. On a GPWBS level chart, there would be two separate views of the flange cost -- as flanges (level 8, commodity) and as part of a piping system (level 3, functional system).

Figures 18 and 19 show other ship-wide roll-up purchase orders similar to the first example, but for other systems (Fire Extinguishing System/SWBS 555 and Sounding Tubes, Vents & Overflows/SWBS 506).

APPLICATION OF GPWBS TO OTHER CURRENT R&D EFFORTS

The GPWBS is the integrator that provides the linkage between the various projects currently underway under the Mid-Term Sealift Ship Technology Development Program. An overview of this program may be found in reference [11]. The Generic Build Strategy, Production-Oriented Design and Construction (PODAC) Cost Model, and Engine Room Arrangement Modeling (ERAM) tasks will use the GPWBS to enhance inter-project communication and data transfer, and as a test case for the interdisciplinary use of a single, unifying work breakdown structure.

In addition to this inter-project integration role, the GPWBS is a fundamental element of the PODAC Cost Model, having been designed from the outset to be used as its information structure. This on-going GPWBS implementation in ship cost estimating is further discussed in the Conclusions section below.

TRANSFERRING TO INDUSTRY AND GOVERNMENT USERS

The completed GPWBS was presented by project team members to their respective organizations, but it was not within the project scope for the team to directly present it to other organizations. Instead it was planned to provide an instruction manual.

This task was carried out by the University of Michigan Transportation Research Institute (UMTRI), who discussed training needs with the training staff of team member shipyards. It was decided that a self-learning manual, with a computer aided interactive version, would be the best way to accomplish transfer of the GPWBS to the user community.

The self-learning manual was completed and distributed to the industry and the Navy. The computer version was not completed due to time constraints, but will be completed under new funding, which will also enlarge the guide to include examples of the use of the interim product tables.

In addition, the use of the GPWBS is currently being taught in two professional short courses offered by UMTRI under the sponsorship of the National Shipbuilding Research Program. Future shipbuilders are learning the use of the GPWBS in the Marine Systems Manufacturing course in the Department of Naval Architecture and Marine Engineering, University of Michigan.

Work Order Record	Work Order Data
Job Number	CX-333
Group Number	17
Sub-Group Number	F3
Item Number	01
Block Number	
Zone Number	02-083-1S
Weight	
Description	Install Misc. Outfit
Quantity	
UoM	
Estimated Man-hours	
Planned Start Date	
Planned Complete Date	
Actual Hours	
Actual Start Date	
Actual Complete Date	

Generic PWBS Data Record

	Product								
Ship Type	Hull No.	Zone	S/O Ind.	I/P Ind.	Long	Vert.	Tran.	Stage	Work Type
LSD	2379	D	Z	Z	01	01	2	OB	HO
			(1)	(2)	(3)	(4)	(5)		

(1) Structure / Outfit Indicator

(2) Interim Product Indicator

(3) Longitudinal Location

(4) Vertical Location

(5) Transverse Location

Figure 13. Sample work order record mapped to GPWBS, miscellaneous outfit.

Work Order Record	Work Order Data
Job Number	CX-333
Group Number	17
Sub-Group Number	F3
Item Number	01
Block Number	
Zone Number	03-099-1C
Weight	
Description	Install Misc. Fittings
Quantity	
UoM	
Estimated Man-hours	
Planned Start Date	
Planned Complete Date	
Actual Hours	
Actual Start Date	
Actual Complete Date	

Generic PWBS Data Record

	Product								
Ship Type	Hull No.	Zone	S/O Ind.	I/P Ind.	Long	Vert.	Tran.	Stage	Work Type
LSD	2379	D	Z	Z	02	03	0	OB	HO
			(1)	(2)	(3)	(4)	(5)		

(1) Structure / Outfit Indicator

(2) Interim Product Indicator

(3) Longitudinal Location

(4) Vertical Location

(5) Transverse Location

Figure 14. Sample work order record mapped to GPWBS, miscellaneous fittings

.

Work Order Record	Work Order Data
Job Number	CX-333
Group Number	46
Sub-Group Number	01
Item Number	02
Block Number	501
Zone Number	
Weight	
Description	Weld Pipe in LO unit
Quantity	
UoM	
Estimated Man-hours	
Planned Start Date	
Planned Complete Date	
Actual Hours	
Actual Start Date	
Actual Complete Date	

Generic PWBS Data Record

	Product								
Ship Type	Hull No.	Zone	S/O Ind.	I/P Ind.	Long	Vert.	Tran.	Stage	Work Type
LSD	2379	M	Z	U	00	00	0	OU	UC
			(1)	(2)	(3)	(4)	(5)		

(1) Structure / Outfit Indicator

(2) Interim Product Indicator

(3) Longitudinal Location

(4) Vertical Location

(5) Transverse Location

Figure 15. Sample work order record mapped to GPWBS, lube oil pipe welding.

Purchase Order Record	Work Order Record
Job Number	CX-333
Group Number	06
Sub-Group	01
Item Number	00
Weight	
Description	Bilge and Ballast Sys
SWBS Ref	
Quantity	
UoM	
Total Cost	

Generic PWBS Data Record

	Product														
Ship Type	Hull No	Zone	S/O Ind	I/P Ind	L	V	T	Assy	S-A	Part	C C	Stage	Work Type	SWBS
LSD	2379	W	O	F	0	0	0	0	0	0	0	OU	UC	529
		Notes:	1	2	3	4	5	6	7	8	9			

(1) Structure/Outfit Indicator
(2) Interim Product Indicator
(3) Longitudinal Location
(4) Vertical Location
(5) Transverse Location
(6) Assembly
(7) Sub-Assembly
(8) Part
(9) Commodity/Component

Figure 16. Sample purchase order record mapped to GPWBS, rolled up to Bilge and Ballast System level.

Purchase Order Record	Work Order Record	Generic PWBS Data Record

Job Number	CX-333
Group Number	06
Sub-Group	23
Item Number	03
Weight	
Description	Flanges (in Distilled*
SWBS Ref	
Quantity	
UoM	
Total Cost	

* in distilled water system

	Product													
Ship Type	**Hull No**	**Zone**	**S/O Ind**	**I/P Ind**	**L**	**V**	**T**	**Assy**	**S-A**	**Part**	**C C**	**Stage**	**Work Type**	**SWBS**
LSD	2379	W	M	F	0	0	0	0	0	0	0	OU	UC	531
		Notes:	1	2	3	4	5	6	7	8	9			

(1) Structure/Outfit Indicator
(2) Interim Product Indicator
(3) Longitudinal Location
(4) Vertical Location
(5) Transverse Location
(6) Assembly
(7) Sub-Assembly
(8) Part
(9) Commodity/Component

Figure 17. Sample purchase order record mapped to GPWBS, commodity level.

Purchase Order Record	Work Order Record	Generic PWBS Data Record

Job Number	CX-333
Group Number	06
Sub-Group	14
Item Number	00
Weight	
Description	Fire Ext Sys
SWBS Ref	
Quantity	
UoM	
Total Cost	

	Product													
Ship Type	**Hull No**	**Zone**	**S/O Ind**	**I/P Ind**	**L**	**V**	**T**	**Assy**	**S-A**	**Part**	**C C**	**Stage**	**Work Type**	**SWBS**
LSD	2379	W	Z	F	0	0	0	0	0	0	0	PR	MA	555
		Notes:	1	2	3	4	5	6	7	8	9			

(1) Structure/Outfit Indicator
(2) Interim Product Indicator
(3) Longitudinal Location
(4) Vertical Location
(5) Transverse Location
(6) Assembly
(7) Sub-Assembly
(8) Part
(9) Commodity/Component

Figure 18. Sample purchase order record mapped to GPWBS, rolled up to Fire Extinguishing System level.

Purchase Order Record	Work Order Record	Generic PWBS Data Record

Job Number	CX-333
Group Number	06
Sub-Group	14
Item Number	00
Weight	
Description	Tank Vents
SWBS Ref	
Quantity	
UoM	
Total Cost	

	Product													
Ship Type	**Hull No**	**Zone**	**S/O Ind**	**I/P Ind**	**L**	**V**	**T**	**Assy**	**S-A**	**Part**	**C C**	**Stage**	**Work Type**	**SWBS**
LSD	2379	W	M	F	0	0	0	0	0	0	0	PR	MA	506
		Notes:	1	2	3	4	5	6	7	8	9			

(1) Structure/Outfit Indicator
(2) Interim Product Indicator
(3) Longitudinal Location
(4) Vertical Location
(5) Transverse Location
(6) Assembly
(7) Sub-Assembly
(8) Part
(9) Commodity/Component

Figure 19. Sample purchase order record mapped to GPWBS, rolled up to Tank Vents System level.

CONCLUSIONS

The GPWBS system was developed by a joint industry/government/academia team. The team synthesized practical shipbuilding know-how with concepts resident in the technical and academic literature to develop a new system.

The system was validated by testing it on actual shipyard work orders and purchase orders which were furnished to the team by a large U.S. shipyard. It was found that the GPWBS can provide good production information visibility for a variety of technical and management purposes. In addition, managers at a large overseas shipyard reported that the GPWBS fit their practice and data quite well.

The progress made towards a generic product-oriented work breakdown structure for shipbuilding has significant potential for build strategy development, cost estimating, design for production, and integration of current Mid-Term Sealift R&D projects.

Build Strategy Development

This GPWBS formalizes the logic and structure of the methods applied under current shipbuilding practice worldwide. It is generic in the sense that it has not copied any one shipyard structure. However, the outcome is such that any shipyard can identify the components of their WBS within it. Build strategies can be facilitated by the GPWBS structure because it systematizes the main components that must be addressed in the strategy. The three axes in the GPWBS bring attention to the individual aspects that drive the build strategy without loosing sight of the integrated structure.

Cost Estimating and Design for Production

Cost model development is the GPWBS application that is being pursued most intently right now. The GPWBS is already being implemented by at least one large shipyard for the development of new tools for ship cost estimation under the PODAC Cost Model project. Use of the GPWBS offers several significant advantages in this area:

- The system provides a conversion tool which enables information on past newbuildings to be converted into a common format for ready use on future projects.
- It enables the development of new estimating processes which will produce ship estimates based on how production builds the ship.
- Under GPWBS, return costs can now be used to validate the cost estimating relationships that produced the estimate.
- Finally, with the above processes in place, it becomes possible to correctly identify cost drivers and their impacts so that designers can design more producible, lower cost ships.

The PODAC Cost Model is using the GPWBS as its data structure and has validated it using shipyard-supplied data. Seven complete ship-sets of estimated cost and return cost data, including contract changes, have been mapped from the shipbuilder's WBS into the GPWBS. No need for modification of the GPWBS has arisen. Further development of the GPWBS for the purposes of cost model development are currently under way and consist of taking the Interim Product Catalog to a greater level of detail.

Integration of Mid-Term Sealift R&D projects

The GPWBS project team included members of the PODAC Cost Estimating Model. The PODAC Cost Model used the GPWBS as its foundation.

The Engine Room Arrangement Model (ERAM) project is developing three merchant vessel engine room designs. The project team must use trade-off analysis and comparative cost estimating in the evaluation of these designs. The ERAM team plans to use the GPWBS for their interim product classification and coding, and for their production-oriented design decisions.

RECOMMENDATIONS

More detailed development of the GPWBS structure's

Interim Product Catalog is needed to fully realize the concept for use in early stage design, contract design, zone layout, production engineering, cost estimation, and "design for ownership." This work is currently taking place in support of the PODAC Cost Model and the Generic Build Strategy projects.

Programs such as ATC, AOE(X) and SC21 could be excellent opportunities for early-stage naval applications of the GPWBS. In addition, the Navy should consider using the GPWBS to model the work breakdown structures of the builders of the LPD-17 class.

A particularly valuable GPWBS application for both shipyard managers and Navy ship acquisition managers would be ship procurements in which vessels of one class are constructed at more than one shipyard. Multi-yard procurements have often been done for naval surface combatants and certain other kinds of warships. One class, multi-yard procurements are also sometimes done in the international merchant shipping industry and the GPWBS could be a good tool for inter-yard cooperation in these cases.

The Navy's functional systems-oriented work breakdown structure evolved over many years. This new generic product-oriented work breakdown structure should be implemented and evolved in a similar manner. The author's hope that the GPWBS will prove a valuable enabler, opening the door to significant process development in our shipbuilding community.

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CE Or Not CE - That Is The Question

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ABSTRACT

There is tremendous interest in Concurrent Engineering (CE), or Integrated Product and Process Development (IPPD), Integrated Product Teams (IPTs) and other related approaches by U.S. Navy and other U.S. shipbuilders as they look for ways to improve productivity and quality, lower costs and shorten time to delivery.

Unfortunately, as formally defined, CE is not for everyone. The full implementation of CE requires such radical rethinking of and changes in the whole operation of a shipbuilder that many will be unable or unwilling to implement CE. Does this mean that such shipbuilders will be unable to capture shipbuilding orders from the international commercial shipbuilding market? Fortunately not! There are many world class shipbuilders that do not use the formally defined CE approach.

The paper examines the practices of a number of world class shipbuilders and compares them to the CE approach. It then details an approach, Situational Design (SD), based on the concept of applying appropriate techniques and tools to suit the situation. It is also based on the use of a Shipbuilding Policy for each shipyard and a Build Strategy for each ship. It offers this alternative as a way for U.S. shipbuilders to achieve the stated goals of CE without the need to make the radical changes and face the associated risk of a full CE implementation.

NOMENCLATURE

CE	Concurrent Engineering
IPPD	Integrated Product and Process Development
IPT	Integrated Product Team
TQM	Total Quality Management
SD	Situational Design

INTRODUCTION

How can such a question as the title be asked at this symposium? There are books, articles and consultants that all state, to be successful today, companies need to implement Concurrent Engineering (CE). Is this right? Maybe not! It is also timely to ask it as many companies are asking this very question as they investigate and consider how they can improve their performance. Is it possible that there is a way to achieve the high quality, low cost and short delivery time by selectively applying some of the approaches covered by the CE philosophy, without undertaking the radical changes that CE requires? It is hoped that this paper will show that there is.

The author is a proponent of CE and has used it successfully in a number of applications and has helped others to implement it. However, like most remedies, it is not for every company.

The hypothesis of this paper is that while CE can be beneficial and can have a place in the shipbuilding process, it may not be necessary for all stages nor is it the solution for every company. Fortunately, there are other ways to reach the goal of high quality, low cost and short design and build times.

An alternative based on applying the best approach for each situation, or Situational Design (SD) is offered.

To use this alternative approach, it is necessary to benchmark successful practice in many companies. The best approach for a given situation may be one, which is now considered part of CE. It has been suggested by a friend that what is being proposed is the modification of the formally defined CE approach to suit shipbuilding. A number of approaches are discussed, including the Build Strategy approach and suggestions on their use in shipbuilding are provided.

Most books on CE describe the benefits, but also emphasize that CE is not easy to implement, nor is success guaranteed. Many companies have tried to implement CE and failed. Others were unable to sustain the implementation from one project to the next. It has been stated [1] that if a company has tried to implement Total Quality Management (TQM), and failed or even considered it and decided it was not for them, it is pointless for them to even contemplate CE, as it is built on many concepts of TQM.

If one visits successful European and Japanese shipbuilders, the absence of many of the CE attributes is very noticeable. That is, they do not use collocated cross-functional teams and participation of all functions in the early design stages. This is because they do not need them. They do not have the problems to begin with that CE can be used to overcome. Their existing way of working does not have narrow work specialization and department stove pipes with their resulting adversarial relationships, self-interest and internal competition. In addition, a shipyard's processes and desired production practices are well known by their designers.

A number of U.S. shipbuilders are trying to enter the world commercial shipbuilding market, and this raises major challenges for them, such as; how to shorten delivery time, reduce ship prices, and improve the world's perception of U.S. shipbuilding quality.

Some of these U.S. shipyards are looking to CE to assist them meet and overcome the challenges.

The paper first presents a brief description of CE, then discusses some of the difficulties in implementing it. Next, the

type of companies that are successful CE users are examined and the differences between them and the shipbuilding industry are considered. Then the alternative Situational Design (SD) approach is presented. Finally Conclusions and Recommendations for the use of SD are presented.

WHAT IS CE

CE was developed by the U.S. Air Force as part of their Advanced Manufacturing Research. The Air Force wanted to know how some foreign and U.S. companies were able to develop products and deliver them to market faster than most companies. While the Air Force has been successful in applying it to their high cost and long product development cycle situation, in general, its greatest success has been in industries where products may have development cycles of years but delivery cycles of days and even hours, such as the electronic and related industries.

CE is much more than parallel development or the application of a few "in vogue" tools. By definition, it is a totally integrated, concurrent development of product and process design using collocated, cross-functional teams to examine both product and process design from creation to disposal. The essential tenets of CE are customer focus, life cycle emphasis and the acceptance of design ownership and commitment by all team members. There is no longer any engineering problem or purchasing problem. Each problem in any area becomes a problem of the whole team.

All these approaches can be helpful if applied well, but many companies fail to achieve the anticipated benefits. This is most often due to the lack of a logical and integrated implementation sequence that starts from where a company actually is and moves systematically toward the company's long-term goals.

The main objective of CE is to shorten time from order to delivery for a new product at lowest cost and highest quality.

Experience with CE shows it can be of the magnitude required by U.S. shipyards to become competitive in the international commercial shipbuilding market. Customer satisfaction has been improved by 100%, cost reduced by 30% and reduction in design and construction time of 50% [2]. Even though this is a process approach, its success depends on the willingness of people in an organization (top to bottom) to change the way they think and behave. Thus the full implementation of CE offers the potential for big payoff.

CE is not new. The original definition of CE was published in 1970 [3]. Many of the techniques and tools used in CE have been around much longer than CE. However, CE packaged them into an integrated philosophy. This packaging approach can be useful when people do not use the individual techniques and tools, to force them to use them. It is also useful when it is necessary to refocus the efforts of a company, industry and even a country.

CE proponents keep mentioning walls between departments and passing information over the wall. This is one result from the U.S. emphasis on work specialization and is a management problem (organizational design and behavior). CE is an "invention" to overcome the problem. It is suggested that it would be better to eliminate the problem instead. Walls can spring up between cross-functional teams and be just as insidious as walls between departments.

The biggest challenge in implementing CE is being able to successfully bring about the foundation wrenching changes that are necessary in the organization structure and management without destroying the organization. It does not appear, from the experience of many companies, that CE can be implemented gradually and gracefully. In most cases the "all or nothing" approach was required.

The next two biggest challenges in implementing CE are the need to change the company's culture and way of operating. They are both required and reinforce each other. The most visible is the operational change (the way things are done). While it may seem that a company's culture would be visible, this is not so. There are many underlying and conflicting influences that result in a company's "visible" culture. It takes considerable skill and effort to analyze a shipyard's culture, but this is an essential part of the management of change. The change in culture must match the desired mode of operating.

Typical changes require moving from:

- department focus to customer focus,
- directed individual or group to coached team,
- individual interests to team interests,
- autocratic management to leadership with empowered followers, and
- dictated decisions to consensus decisions.

CE involves increased expenditures of time and money "up-front" with the potential benefit of overall improvement in time and cost from better product design.

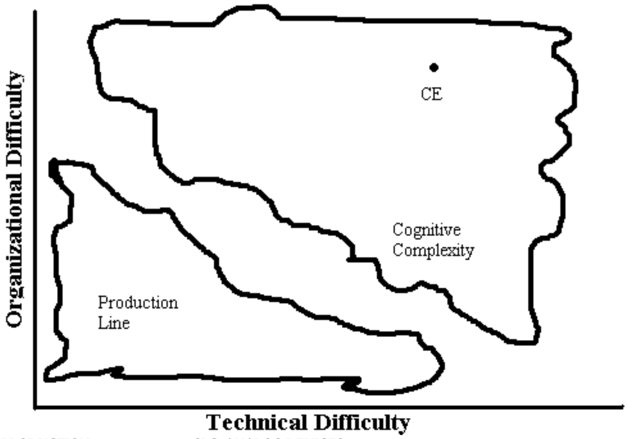
CE DIFFICULTIES

The benefits derived from CE can be radical, but the effort required to bring about the changes required to implement CE can be even greater. These changes are not easy and result in major difficulties for the use of CE. Many companies that attempted to implement CE failed to accomplish it or to achieve any benefit from the attempt. In many of these cases the situation has been well researched and documented in the proceedings of conferences addressing CE and are listed in [1]. These can be read and used by other companies to help understand the extent of the changes that are needed. The most common reason for the failures was the inability of management to effectively manage the introduction of the required changes in their processes and culture.

Ideally, CE involves all the product development participants, including the customer and the company's suppliers, in a team environment, at the start and throughout the design of the product and its processes.

This all-encompassing involvement of all stakeholders is what differentiates CE from other recent improvement approaches. When companies undertake improvement change, they typically want to start with some quick wins. This usually leads them to change something in production where the impact of change can be easily seen in new equipment and/or processes. This can be seen from Figure 1, which shows areas of change on coordinates of Organizational Difficulty versus Technical Difficulty. It shows that production improvement changes are normally made in the low to medium difficulty region and that CE is in the high organizational and medium technology difficulty region. The problem with this approach is that it rarely produces the anticipated improvement because the systems that support production have not improved or even made

any changes. This causes an imbalance in a previously balanced system and results in departments out of sync



PRODUCTION - LINE   SPC, ANALOG DEVICES
SHORT TIME TO IMPROVE/INFLUENCE

COGNITIVE - COMPLEXITY   NEEDS COORDINATION
LONG TIME TO IMPROVE/INFLUENCE

Figure 1 -
Organizational and Technical Difficulty Relationship

with each other. For any change to be successful all of
the stakeholders, that is anyone that the change will impact, must be involved, and compatible and supportive changes made in all impacted departments.
There are also two camps in the improvement change
field. The first believe that low technology changes must be undertaken before any high technology change is attempted. The second proposes the exact opposite and believes that technology can overcome organizational problems.

The successes of CE are well stated in the many CE books and conference papers. The following are offered as difficulties with CE that can be avoided by the SD approach.

- CE costs more for design and planning and for one-off or small product quantity, and may not be cost competitive or give the shortest design and build time.
- CE is often undertaken only when a company has reached a crisis of survival and then it is often too late.
- CE with its cross-functional teams needs team rewards instead of individual rewards. This has proven to be very difficult to implement.
- Mid-management resists and is reluctant to give up authority to teams.
- Many companies find the investment in systems and personnel change needed to implement CE unacceptable.
- Companies must have a culture that allows changes to work.
- The cooperation, trust and sharing required to successfully implement CE is lacking from current U.S. shipbuilding company cultures.
- To establish teams due to existing cultures that focus on the individual not the group, based on the deep routed U.S. belief in independence.
- Many U.S. shipbuilders are still "telling" organizations, where managers tell workers what to do and do not expect to be challenged.
- Reluctance of individual team members to accept team consensus.
- Need for collocation of teams.
- Lack of a permanent home for team members.
- Lack of clear career path, what happens after team completes task?
- Uncertainty and ambiguity in roles/tasks.
- Resistance to collaboration - communication, cooperation and complete sharing.
- Workers are unable or unwilling to learn new skills.
- Workers are unable or unwilling to accept additional responsibility.
- Need for extensive training of all employees.
- Getting customers, external and internal, on cross-functional teams.
- Requires changes that are transformational, that is fundamental, organization wrenching and far reaching.
- Sustaining the use of CE throughout the life of a product.
- CE is a non-traditional approach to the product development process, and while many of its concepts are logical, its implementation may be perceived by many as radical change and thus generate significant barriers to its acceptance and support.

A excellent discussion of this aspect of CE implementation was presented by Parsaei and Sullivan, [4]. Figure 2 is taken from that reference. It shows the many modes of failure and their relationship to the phases of implementation as well as the influence of management and employees at each mode.

WHO USES CE

The early users of CE were companies that had long product development times but short build times and large quantities of each product to manufacture. These companies were in industries in which time to market was a major success criterion. Being able to design, prototype and deliver products even just a day before your
competitors could mean the difference between success and failure of a product. The CE literature has many examples of stories about electronic and consumer

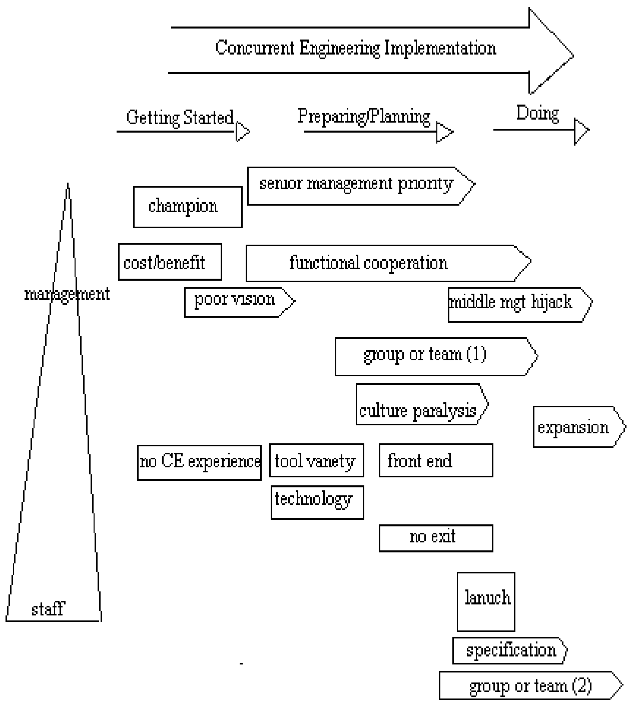


Figure 2 - CE Common Failure Modes

products experiences with CE.

Industries, such as automotive and aerospace, that had even longer development time, involved expensive prototyping, but still had relatively short build times found that CE could reduce the development and prototype time and thus the total time from concept to delivery.

Finally industries, such as shipbuilding and general construction, have latched onto CE as a way to reduce both design and build times and cost of small quantity products.

DIFFERENCES BETWEEN SHIPBUILDING AND OTHER INDUSTRIES

While the "we are different " argument is normally used as a defense against trying something new, it does have some relevance with regard to the implementation of CE. There are significant differences between the shipbuilding industry and other industries that have reported benefits from the use of CE, and it is worthwhile to identify and fully understand them. This will allow shipbuilding management to make a better decision regarding the use of CE.

In some industries the final customer is far removed from the OEM. The automotive industry is such an example where there are distributors and car dealers between them and their customers. Their marketing department uses focus groups and surveys as well as feed back from trade shows. However, the single customer is never considered. It is most unlikely that the typical international commercial ship owner will be willing to commit personnel to a U.S. shipbuilders CE team for 1 to 2 years when foreign shipbuilders can deliver an acceptable ship in the same time without the need and therefore cost of this extra personnel commitment.

Ship engineering has always been parallel development and ship production moved from sequential to parallel some years ago. Block construction and zone outfitting is the move from just parallel to integrated.

CE is the concurrent design of product and process and makes sense when each new product needs completely new processes. Ships do not change much. They are made up from many components that are the same or similar. Shipbuilding facilities are not designed for a single product but are designed to be able to build a range of ship types and sizes. Thus it is not necessary to have cross-functional teams to develop both product and process design concurrently. Functional groups can effectively design the product to suit the previously documented existing processes. Therefore, in shipbuilding the product is usually designed to fit the available processes rather than design new processes.

Success for a new product depends more on making design aware of the processes than getting process designers and product designers together at the same place and time.

Ships are not built on spec or for inventory as are electronic, consumer and automotive products. In shipbuilding, the final customer is in direct contact with the shipbuilder and not separated by distributors and stores.

Compared to other industries there is little uncertainty. Shipbuilders know who will buy and what is wanted and usually do not start until a contract is signed. In shipbuilding there is no need for new models every 2 to 3 years with the resulting changes in processes.

Figure 3: Typical Development Times

YEAR	-5	-4	-3	-2	-1	1	2	3
AUTOMOBILE W/O CE		Product &	Process	Development	Prototype	← Production		
AUTOMOBILE WITH CE				IPPD & 3D	Product Model	← Production		
			←Contract	Award				
AIRCRAFT W/O CE		Product &	Process	Development	Prototype	← Production		
AIRCRAFT WITH CE				IIPD & 3D	Product Model	← Production		
						←Contract	Award	
NAVAL SHIP W/O CE	Formulated Need Prepare Concept & Prel Design				Cont Design	Detailed Design & Production		
NAVAL SHIP WITH CE			IPPD For PRE CD Activities		CD	Detailed Design & Production		
						←Contract	Award	
COMMERCIAL SHIP W/O CE US					Own Dev CD	Detailed Design & Production		
COMMERCIAL SHIP W/O CE Foreign					OD CD	Det Design & Production		
KEY	IPPD	INTEGRATED PRODUCT AND PROCESS DEVELOPMENT						
	CD	CONTRACT DESIGN						
	OD	OWNER DEVELOPMENT						

Cradle to grave life cycle focus is most unlikely in commercial shipbuilding as it is normal for the shipbuilder to never see or have any involvement with the ship past the warrantee period. It also means that the designer and even his company will not be involved in these decisions during the ship's operating life.

This does not mean that designers of commercial ships should ignore life cycle costs. Designers must do everything within their control to ensure that ships built will be a success for ship owners.

Industries that appear to benefit most from CE are those with long development and short build times. For example 3 years development, 1 year prototype and 1 month, or less, build times. Commercial shipbuilding is not like this. It has almost equal design and build times with considerable overlapping of design, planning,
purchasing and construction. This is clearly shown in Figure 3.

While the use of 3-D product modeling has the potential to provide virtual prototypes, most shipbuilders are still unlikely to do this, in the foreseeable future, because of its time and cost. In the large product quantity industries, such as automobile and even aircraft, years are taken to design and billions of dollars are spent on special jigs and tooling for each new product. If the design and process are not compatible, considerable additional cost and delay could result. Therefore the product goes through extensive prototyping and testing of functions, as well as build processes, before going into full production.

In this regard, shipbuilding is completely different. It is a small quantity industry that rarely uses prototypes. Construction usually starts before design is complete, even for military ships.

While the time for pre-construction activities can be impacted by approaches such as CE, the build time is more dependent on having a continuous throughput of ships than anything else.

SITUATIONAL DESIGN

There are shipyards in Europe and Japan that build 4 to 6 ships per year, with typical build times of 11 months, with a technical work force of 250 and a production work force of 800 employee's [5]. They are obviously successful from the point of view of time, but it is not possible to say in if they are financially successful due to unclear position
of subsidies. None of them use the formal CE approach.

However, they all have a number of things in common, namely:

- simple functional organization ,
- restricted product range,
- complete documented shipbuilding practice
- focus on one assembly site,
- stable processes,
- effective application of new technology, and internal collaboration rather than internal competition.

They do not have to use CE as they do not have the problems that CE has been developed to overcome. However, these foreign shipyards do not build military ships or even government owned ships, so they are not subject to the long acquisition process generally associated with such ships.

They have used the value generated method, which constantly eliminates non-value added activities, over many years and the result is that they are already a "lean production" organization. They have further become a virtual shipbuilder in that they determined their core competencies and focused on performing them the best they could, and subcontracting most everything else.

This knowledge of foreign shipyard approaches can be used to offer an alternative to the full implementation of CE through the application of Situational Design (SD). SD uses the philosophy that, in shipbuilding, as the product processes do not change for every new product, the need for collocated cross-functional teams for all stages of the design of each new product is eliminated.

Most are familiar with situational management and leadership. For those that are not, it is simply applying different management techniques and leadership styles depending on the situation. Therefore SD is the application of the best "design approach or tool," including some of them now included as part of CE, to fit the situation. An SD decision matrix can be developed to guide the designer as to what approach to
use for different situation problem and stage. The selected approach would change as the situation changed.

A book on organizational flexibility [6] introduced the concept of organizational circles, cones and pyramids and their appropriate use. Table I is developed from the book. Its usefulness to the shipbuilding situation is also shown in the Table. The circle, which emphasizes everyone's involvement in product definition, is used for all design up to bid.

APPROPRIATE ORGANIZATION STRUCTURE	**CIRCLE**	**CONE**	**PYRAMID**
FUNCTION	CLARIFY PROBLEMS GENERATE ALTERNATIVES	PLAN FOR ACTION DESIGN SYSTEMS	IMPLEMENTING PLANS ACCOMPLISH GOALS
ACTIVITY	THINKING TALKING CLARIFING CREATIVE	PLANNING DESIGNING BUILDING	DOING ACTING COMPLETING
PLANNING LEVEL	STRATEGIC	TACTICAL	OPERATIONAL
BUILD STRATEGY APPROACH LEVEL	SHIPBUILDING POLICY	BUILD STRATEGY	
APPROPRIATE APPOACH	CONCURRENT ENGINEERING	PROJECT MANAGEMENT	DEPARTMENTS WORK TEAMS

Table I - Situation Design Guide

The cone, which emphasizes priorities and responsibilities, is used for all remaining design and planning and the pyramid, which emphasizes implementation and monitoring of the design and plan, is used for the actual building of the ship.

Another important aspect is that the different approaches require different management methods and leaders. While this may seem just another view of situational leadership, there is an important difference. Situational leadership recommends that a single manager apply different leadership styles to different situations.

The Flexible Organization approach shows that different managers will be required to fill the different circles, cones and pyramids depending on their predominant leadership style. What that means is that managers must be carefully selected for the different phases.

A useful tool in SD is the Design Structure Matrix [7], which identifies the information flow between activities. This matrix helps to identify:

- information flow between activities;
- best sequence for activities;
- sequential, parallel and coupled activities;
- a logical view of the total process;
- later sequenced activities that provide input to earlier activities; and
- required make-up of cross-functional teams, and impact of changes.

By observing the information flow relationships and the lack of or presence of "clusters," the potential for grouping the activities and applying the best approach (sequential, parallel or coupled) to them is made visible. This can be seen from Figure 4 which shows the author's adaptation of the original matrix as well as in Figure 5 which shows the benefit of the Shipbuilding Policy.

A major factor in the success of the European and Japanese shipyards is the above mentioned documentation of their shipbuilding practices. As expected the extent of the documentation varies depending on the needs of the various shipyards, but they all have it.

The SD approach tries to emulate the successful, simply organized, world class shipyards. It identifies three phases in the ship development cycle, namely Product Definition, Product Development and Product Construction. It uses the circle approach for product definition, the cone approach for product development and the pyramid approach for product construction. It uses many practices now considered part of CE such as cross-functional teams in the product definition phase, project manager and functional groups in the product development phase and either functional groups or work teams in the product construction stage depending on production department culture and skill and education level of the workers. Finally, it uses the formal Build Strategy approach as the foundation on which to build the rest of the system.

The shipbuilding practice books used in Japanese shipyards are well known, but the Build Strategy approach is not as well known, even with the NSRP report on the subject [5]. The A&P Appledore shipyards, in Britain, developed the formal Build Strategy approach just before the British shipbuilding industry was nationalized in the late 70's. It was

		1	2	3	4	5	6	7	INPUTS
PRODUCTION RANGE	1	**1**	↑			↑	↑	↑	4
FACILITIES	2	↓	**2**	↑		↑	↑	↑	5
PROCESSES	3	↓	↓	**3**		↑	↑	↑	5
SHIP DEFINITION	4	↓	↓	↓	**4**		↑	↑	5
WORK STATIONS	5	↓	↓	↓		**5**	↑	↑	5
PWBS	6	↓	↓	↓	↓	↓	**6**	↑	6
INTERIM PRODUCT CAT	7	↓	↓	↓	↓	↓	↓	**7**	6
OUTPUTS		6	6	5	2	5	6	6	

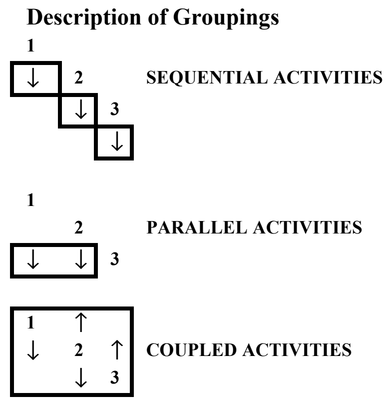


Figure 4 - Design Structure Matrix for Shipbuilding Policy

further developed by the nationalized British Shipbuilders. [8,9]

The formal Build Strategy approach was the subject of an NSRP study [5]. For completeness it is briefly described in this paper with emphasis on the Shipbuilding Policy, for reasons that will become apparent.

A Build Strategy is an agreed design, engineering, material management, production and testing plan, prepared before work starts, with the aim of identifying and integrating all necessary processes.

A Build Strategy is a unique shipbuilding tool. It provides a holistic beginning to end perspective for capturing the combined design and shipbuilding knowledge and processes, so they can be continuously improved, updated, and used as both reference and training tools.

The performance of any endeavor will be improved by improvements in communications, cooperation and collaboration. A Build Strategy improves all three. It communicates the intended total shipbuilding project to all participants. This communication fosters improved cooperation as everyone is working to the same plan. It improves collaboration by involving most of the stakeholders (interested parties) in its development.

The Build Strategy approach incorporates other pre-requisites. This is because, while a Build Strategy can be produced as a stand alone document for any ship to be built by a shipyard, it will be a great deal thicker and will take a lot more effort to produce than if certain other documents are will not be available. This is clearly shown in the Design Structure Matrices for the Build Strategy approach with and without a Shipbuilding Policy in Figure 4.The first of these documents is the shipyard's Business Plan, which probably exists, in some form, in most shipyards. A Business Plan sets out a shipyard's ambitions, in terms of desired product range, output and build cycles, for a period of years and describes how the shipyard aims to attain them.

The Business Plan sets a series of targets for the technical and production part of an organization. To meet these targets, a set of decisions is required on:

- facilities development,
- productivity targets,
- production organization and methods,
- planning and contract procedures,
- make-buy and subcontractor policy, and
- technical and production organization.

These form the core of the Shipbuilding Policy which is the other required document. The shipbuilding policy has a hierarchy of levels, which allow it to be applied in full at any time to a particular contract. The shipbuilding policy defines, for the product mix, which the shipyard intends to build, the optimum organization,
and procedures, which will allow it to produce ships efficiently.

The shipbuilding policy also contains the Ship Definition. The Ship Definition is a detailed description of the procedures to be adopted, and the information and format of that information to be produced by each department developing technical information within a shipyard. The ship definition must reflect the manner in which the work is to be performed and make full use of the physical and procedural standards that have been adopted. The ship definition specifies the format and content that the engineering information will take in order to support the manner in which the ships will be built. The engineering information provided to the

WITH SHIPBUILDING POLICY

		1	**2**	**3**	**4**	**5**	**6**	**7**	**INPUTS**
SHIPBUILDING POLICY	**1**	**1**							0
PRELIMINARY DESIGN	**2**	↓	**2**						1
CONTRACT DESIGN	**3**	↓	↓	**3**					2
BUILD STRATEGY	**4**	↓		↓	**4**				2
PRODUCTION DESIGN	**5**	↓		↓	↓	**5**			3
OPERATIONAL PLANNING	**6**	↓			↓	↓	**6**		3
PRODUCTION	**7**	↓				↓	↓	**7**	3
OUTPUTS		7	1	2	2	2	1	0	

WITHOUT SHIPBUILDING POLICY

		1	**2**	**3**	**4**	**5**	**6**	**INPUTS**
PRELIMINARY DESIGN	**1**	**1**						0
CONTRACT DESIGN	**2**	↓	**2**	↑				2
BUILD STRATEGY	**3**		↓	**3**	↑			2
PRODUCTION DESIGN	**4**		↓	↓	**4**			2
OPERATIONAL PLANNING	**5**			↓	↓	**5**		2
PRODUCTION	**6**					↓	**6**	1
OUTPUTS		1	2	3	2	1	0	

Figure 5 - DSMs for Build Strategy Approach with and without a Shipbuilding Policy

production department should only include that necessary for them to perform the work in the assigned work stations.

The description must ensure that the information produced by each department is in a form suitable for the users of that information. The Ship Definition will detail the methods for breaking the ships in the product mix into standard interim products by applying a Product-oriented Work Breakdown Structure (PWBS). It will also incorporate a shipyard's Interim Product Catalog. Areas in which the interim products will be produced and the tools and procedures to be used will also be defined.

An essential prerequisite for successful block and zone approach is the use of PWBSs. An NSRP publication outlined their need, use and the experience of Japanese shipyards [10]. A companion paper to be presented at this symposium reports on more recent developments of PWBSs and interim products (11).

A major objective of the Shipbuilding Policy is design rationalization and standardization. This is achieved by the application of Group Technology and the PWBS to form families of interim products having similar manufacturing requirements.

Most manufactured products are assembled from many components, both manufactured by and purchased by the assembler. All of these components can be viewed as "interim products."

Most shipbuilders view a ship as being composed of many interim products. Each interim product is the output of a work stage, and are combined with other interim products until the ship is complete.

Many shipbuilders have used the interim product concept along with Group Technology to group the interim products for the range of ship types and sizes that they build into families, either by interim product geometry or process. This has resulted in classification and coding of their interim products into a catalog.

Initially, this catalog was simply descriptive, but has grown to become a communication tool for estimators, designers, planners and production workers. Today, interim product catalogs not only describe the product and/or processes, but include preferred process, next preferred alternative process, process required resources, stage of construction, parametric standard times, and any other useful characteristic.

The use of an interim product catalog has many benefits to a shipbuilder. It:

- promotes product and process standardization ,
- simplifies process planning,
- promotes stable processes,
- supports product based estimating, and
- provides a clear definition of process flows.

As such, it is easy to see how the interim product catalog is a natural and essential part of the proposed Ship Definition.

The relationship between the Business Plan, Shipbuilding Policy and Build Strategy is shown in Figure 6.

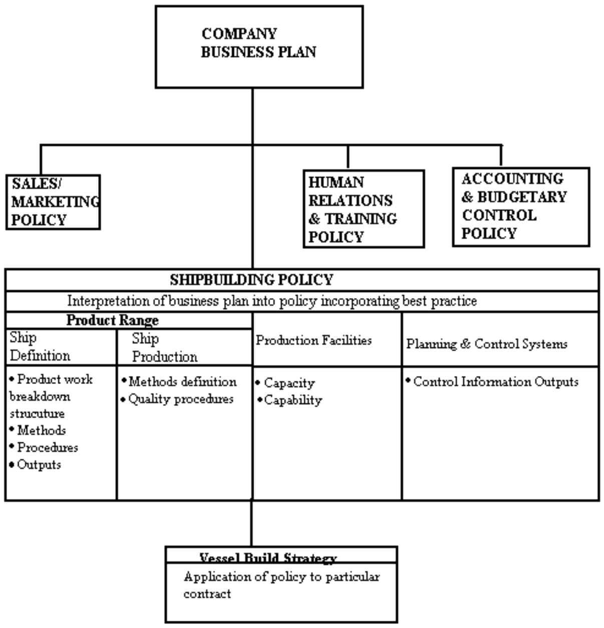


Figure 6 - Relationship of Business Plan, Shipbuilding Policy and Build Strategy

In essence, the Shipbuilding Policy comprises a set of standards, which can be applied to specific ship contracts. The standards apply at different levels:

- Strategic, related to type plans, planning units, interim product types, overall facility dimensions, and so on; applied at the Conceptual and Preliminary Design stages;
- Tactical, related to analysis of planning units, process analysis, standard products and practices, and so on; applied at the Contract and Transition Design stages;
- Operational, related to work station operations and accuracy tolerances; applied at the Detail Design stage.

Work at the strategic level provides inputs to:

- the conceptual and preliminary design stages,
- contract build strategy,
- facilities development,
- organizational changes, and
- the tactical level of shipbuilding policy.

Documents are prepared which address the preferred product range. For each vessel type, the documents include:

- definition of the main planning units,
- development of type plans, showing the sequence of erection, and
- analysis of main interim product types.

The strategic level also addresses the question of facility capability and capacity.

Documentation providing input to the preliminary design stage includes:

- preferred raw material dimensions,
- maximum steel assembly dimensions,
- maximum steel assembly weights,
- material forming capability, in terms of preferred hull configurations,
- "standard" preferred outfit assembly sizes, configuration and weights, based on facility
- capacity, and
- "standard" preferred service routes.

At the tactical level standard interim products and production practices related to the contract and transition design stages, and to the tactical planning level are developed. All the planning units will be analyzed and broken down into a hierarchy of products.

The shipbuilding policy will define preferences with respect to standard:

- interim products,
- product process and methods,
- production stages,
- installation practices,
- material sizes, and
- piece parts.

The capacity and capability of the major shipyard facilities is also be documented. For the planning units, sub-networks are developed which define standard times for all operations from installation back to preparation of production information. These provide input to the planning function.

At the Operational level, a shipbuilding policy provides standards for production operations and for detail design.

The documentation includes workstation:

- descriptions,
- capacity,
- capability,
- design standards,
- accuracy control tolerances,
- welding standards, and
- testing requirements.

For the planning units, sub-networks are developed which define standard times for all operations from

1.0 OVERVIEW
1.1 Objectives
1.2 Purpose and Scope

2.0 PRODUCT RANGE
2.1 Product Definition
2.2 Outline Build Methods

3.0 OVERALL PHILOSOPHY
3.1 Outline
3.2 Planned Changes and Developments
3.3 Related Documents
3.4 Work Breakdown Structure
3.5 Coding
3.6 Technical Information
3.7 Workstations
3.8 Standards
3.9 Quality Assurance
3.10Accuracy Control

4.0 PHYSICAL RESOURCES
4.1 Outline
4.2 Planned Changes and Developments
4.3 Related Documents
4.4 Major Equipment
4.5 Steel Preparation and Subassembly
4.6 Pipe Manufacture
4.7 Outfit Manufacture
4.8 Steel Assembly
4.9 Outfit Assembly
4.10 Block Erection
4.11 Engineering Department

5.0 SHIP PRODUCTION METHODS
5.1 Outline
5.2 Planned Changes and Developments
5.3 Related Documents
5.4 Standard Interim Products, Build Methods,
5.5 Critical Dimensions and Tolerances
5.6 Steel Preparation
5.7 Steel Assembly
5.8 Hull Construction
5.9 Outfit Manufacture
5.10 Outfit Assembly
5.11 Outfit Installation
5.12 Painting
5.13 Services
5.14 Productivity Targets
5.15 Subcontract Work

6.0 SHIP DEFINITION METHODS
6.1 Outline
6.2 Planned Changes and Developments
6.3 Related Documents
6.4 Ship Definition Strategy
6.5 Pre-Contract Design
6.6 Post-Contract Design
6.7 Engineering
6.8 Work Station Documentation

7.0 PLANNING FRAMEWORK
7.1 Outline
7.2 Planned Changes and Developments
7.3 Related Documents
7.4 Strategic Planning
7.5 Tactical Planning
7.6 Operational Planning
7.7 Performance Monitoring and Control

8.0 HUMAN RESOURCES
8.1 Outline
8.2 Planned Changes and Developments
8.3 Related Documents
8.4 Organization
8.5 Training
8.6 Safety

9.0 ACTION PLAN
9.1 Outline
9.2 Projects and Time scales

TABLE II - TYPICAL LIST OF CONTENTS IN A SHIPBUILDING POLICY DOCUMENT

installation back to preparation of production information. These provide input to the planning function.

Because shipbuilding is dynamic, there needs to be a constant program of product and process development. As with all levels of the shipbuilding policy, the standards should be updated over time, in line with product development and technological change. Also, the standards to be applied change over time with product type, facility, and technology development.

Table II shows typical contents of a Shipbuilding policy.

The shipbuilding policy is therefore consistent, but at the same time undergoes through a structured process of change, in response to product development, new markets, facilities development, and other variations.

Again, many of the CE techniques can be effective at this stage to ensure the involvement of all departments.

Therefore, to link current policy with a future policy, there should be a series of projects for change which are incorporated into an overall action plan to improve productivity. Since facilities are a major element in the policy, a long term development plan should exist which looks to a future policy in that area. This will be developed against the background of future business objectives, expressed as a plan covering a number of years.

Many U.S. shipyards and the U.S. Navy are now strong proponents of the Build Strategy approach, but few, if any, of them develop a Shipbuilding Policy. This is difficult to understand as the Shipbuilding Policy is the most important part of the Build Strategy approach.

To be successful in today's international shipbuilding market, a shipyard should design its facilities around a specific product range and standard production methods which are supported by a variety of technical and administrative functions that have been developed according to the requirements of production. These would be described and captured in the Shipbuilding Policy. Then whenever new orders are received only work, which is

significantly different from any previously undertaken needs to be investigated in depth in order to identify possible difficulties. There is no hesitation in getting started as it is known how the shipyard will process all the work from preliminary design through testing and delivery. There is no need for meetings to hammer out new agreements between departments or to “reinvent the wheel. With the processes well known throughout the shipyard, decisions can be made at the appropriate levels, leaving the managers time to work with other managers on new strategic plans.

Without a Shipbuilding Policy key players must meet at the start of each new project to decide what will be done and who will do it.

The next level in the hierarchy defines the set of strategies by which this policy is realized, namely the Build Strategy.

The Build Strategy is a "seamless" document. That is, it crosses all traditional department boundaries. It is an important step in the direction of the seamless enterprise. The most evident benefit is improved communication brought about by engaging the whole company in discussions about project goals and the best way to achieve them.

It should bring up front, and be used to resolve, potential conflicts between departments in areas of design details, manufacturing processes, make or buy decisions, and delivery goals.

It eliminates process or rework problems due to downstream sequential hand-over of tasks from one department to another by defining concurrently how the ship will be designed and constructed.

The Build Strategy:

- applies a company's overall shipbuilding policy to a contract;
- provides a process for ensuring that design development takes full account of production requirements;
- systematically introduces production engineering principles that reduce ship work content and cycle time;
- identifies interim products and creates product-oriented approach to engineering and planning of the ship;
- determines resource and skill requirements and overall facility loading;
- identifies shortfalls in capacity in terms of facilities, manpower and skills;
  creates parameters for programming and detail planning of engineering, procurement and production activities;
- provides the basis on which any eventual production of the product may be organized including procurement dates for long lead material items;
- ensures all departments contribute to the strategy;
- identifies and resolves problems before work on the contract begins; and
- ensures communication, cooperation, collaboration and consistency between the various technical and production functions.

The very act of developing a Build Strategy has benefits because it requires the various departments involved to communicate, and to think rationally about how and where work for a particular contract will be performed. It also highlights any potential problems and enable them to be addressed well before the "traditional" time when they arise.

The shipbuilding policy should be examined in order to ascertain if a ship of the type under consideration is included in the preferred product mix. If such a ship type does fit, then certain items will already have been addressed. These items include:

- outline build methods,
- work breakdown structure,
- coding,
- workstations,
- standard interim products,
- accuracy control,
- ship definition methods,
- planning framework,
- physical resources at shipyard, and
- human resources.

One thing, which is unique to any new ship order, is how it fits in with the ongoing work in a shipyard. The current work schedule must be examined in order to fit the ship under consideration into this schedule. Key dates, such as cutting steel, keel laying, launch and delivery will thus be determined.

Using the key dates other events can be planned. These events are:

- key event program,
- resource utilization,
- material and equipment delivery schedule,
- material and equipment ordering schedule,
- drawing schedule,
- schedule of tests and trials, and
- stage payment schedule and projected cash flow.

Once the major events and schedules are determined, they can be examined in detail to expand the information into a complete build strategy. For example, the key event program can be associated with the work breakdown to produce planning units and master schedules for hull, blocks, zones, equipment units, and systems.

The Build Strategy Document should be used by all of the departments in the shipyard, and a formal method of feedback of problems and/or proposed changes must be in place so that agreed procedures cannot be changed without the knowledge of the responsible person. Any such changes must then be passed on to all holders of controlled copies of the Build Strategy.

CONCLUSIONS

1. Whatever approach is used, the essential ingredient to success in today’s global industries is continuous learning and improvement.
2. To accomplish change it is useful to have a framework or system to provide the required discipline. This is what CE and other approaches based on linking existing tools and techniques do.
3. As defined, CE requires radical changes to the way a company functions, including company culture, management, worker involvement, cross-functional teams, collocation and other management/worker interface aspects, that many companies are unable or unwilling to undertake.
4. CE has been proven to be very beneficial for products that are manufactured in large quantities, have long development time

but short build time, such as cars and electronic equipment. CE has also proven useful for medium quantity products that have long acquisition cycles, such as military aircraft and tanks.

5. CE is currently being applied to small quantity and even longer acquisition cycle warships.
6. The CE approach does not have to be applied cradle to grave. It can be successfully applied to specific stages in a products life cycle. However, it must have clear goals and a clearly defined beginning and end.
7. CE has had a meaningful benefit in bringing the many internal and external players in the naval ship development process together and made them aware of how they need to improve.
8. CE has helped U.S. Navy shorten the pre-contract acquisition time
9. CE has been judged successful in many situations not because it made a good system better, but because it improved a bad situation.
10. Many of the problems that CE is designed to overcome can be resolved by other approaches.

RECOMMENDATIONS

1. Fully understand what a shipyard is trying to do and establish goals before deciding to implement CE.
2. Look at why change is needed.
3. Concentrate on eliminating activities rather than improving them.
4. Look at other alternatives to CE and understand the different levels of change required.
5. Use SD to select the best approaches and integrate them with the Build Strategy approach.
6. Select the alternative that has the best potential for success both in acceptance and improvement.
7. Remember that matching the right response to the situation is critical for success in implementing change.
8. Use the Design Structure Matrix to identify the best sequencing and grouping of activities.
9. CE should be used for activities where "circular" approaches are used, such as the development of the Shipbuilding Policy and even the first time a Build Strategy is prepared.

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Development Of A Production Optimization Program For Design And Manufacture Of Light Weight/High Strength Hull For The Next Generation Of High Speed Craft

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ABSTRACT

There is an interest in introducing a high speed marine vehicle for crew boat service to the offshore oil and gas fields in the Gulf of Mexico. Consequently, it is necessary to develop a light weight hull structure suitable for rapid modular construction. This paper presents the authors' numerical and experimental evaluation of a lightweight aluminum hull panel. An optimization routine was developed to investigate the sensitivity of the design to different structural arrangements. An example of the optimization routine for a stiffened aluminum plate is presented.

INTRODUCTION

The recent increase in oil prices has created a resurgence in oil and gas field development. These new fields are farther offshore and in deeper water. This development is impacting both rig construction as well as field support vessels such as crew boats and offshore supply boats.

Traditionally, crew exchange has been done using helicopters. However the deep water fields are often outside the helicopter's operating range. The helicopters have had to land on near-shore platforms and re-fuel to reach the new offshore fields. These offshore fields are also creating service requirements which are difficult for the helicopter to meet due to their limitations from weather, payload, and fuel capacity.

This situation has opened the possibility of introducing a 30 - 42 knot crew boat for this deep water offshore crew/cargo exchange. This new generation of crew boat can be built in a cost effective manner by taking advantage of advances in ship production technology, especially in the areas of engineering design and manufacturing.

In order to properly develop this high speed crew boat, it is necessary to develop the craft in all four quadrants of the technology cross [1]:

1. Materials,
2. Structure/Construction,
3. Propulsion System, and
4. Hull form - Resistance and seakeeping.

This paper discusses an ongoing research project that focuses on quadrant 2, Structure/Construction. This work is part of a two year research project sponsored by the Gulf Coast Region Maritime Technology Center (GCRMTC).

SERVICE REQUIREMENTS

There has been a gradual evolution in the design of offshore crew boat vessels [2]. With the development of the deep water offshore fields in the Gulf of Mexico, it becomes difficult to make crew changes exclusively by helicopter. Therefore an emerging requirement exists for a 40 - 45 m long, 30 - 42 knot crew boat, capable of meeting the requirements outlined in Table I.

Today a number of 35 - 40 knot high speed aluminum catamarans are operating worldwide [3]. They have become a reliable high speed passenger and cargo transport craft. A catamaran vessel, with its large deck area, is also attractive for offshore crew boat service. At 35 - 40 knots, the crew transfer could be within an acceptable 2 - 3 hour duration.

Vessel Speed	30 - 40 kts
Vessel Cargo	50 - 100 tons max
Vessel Range	500 - 600 miles
Passengers	10 - 12

Table I. Next generation crew boat high speed cargo vessel requirements.

VESSEL DESIGN

The preliminary design of the vessel resulted in the principal particulars listed in Table II.

Catamaran	Units	Value
Length	m (ft)	40 (125)
Beam (overall)	m (ft)	10.5 (34.5)
Beam (hull)	m (ft)	2.743 (9)
Draft	m (ft)	1 (3.33)
Displacement	tons	120 - 150
Speed	knots	35
Material	Aluminum	
Engine	Diesel	

Table II. Vessel Particulars

The half midship section arrangement is shown in Figure 1. The hull form is a surface piercing type. It is to be manufactured in modules which are assembled in a panel line. Since the material flow is critical, the panels would be manufactured from aluminum plate and readily available structural extrusions.

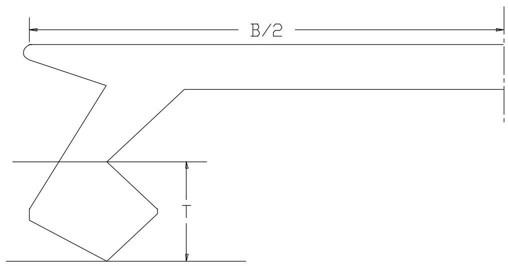

Figure 1. Surface piercing hull form.

HULL PANEL DEVELOPMENT

The hull structure was developed to satisfy three requirements:

1. Classification Rules
   To make this vessel marketable worldwide, it is necessary to satisfy classification society rules such as DNV, Bureau Veritas, as well as the new ABS rules for high speed craft [4,5].
2. Modular Construction
   The hull structure was designed to be manufactured from aluminum stock plate and readily available aluminum structural extrusions. This is reflected in the hull panel geometry summarized in Table III.
3. Floating Frame Arrangement
   The third aspect of the structural design is to incorporate the floating frame. The floating transverse frame is welded on the upper flange of the longitudinals. It offers a reduction in welding man-hours and fit-up at some loss of panel stiffness.

The resulting panel is shown in Figure 2. The details of the panel geometry are summarized in Table III.

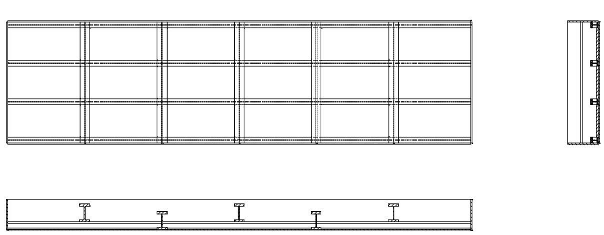

Figure 2. Floating frame hull panel.

Item	Value/Description
Material	Aluminum
Length	4.572 m (15 ft)
Width	1.829 m (6 ft)
Plate thickness	.794 cm (.3125 in)
Longitudinal stiffeners	7.62 cm (3 in) Al I-beam
Transverse stiffeners	17.78 cm (7 in) Al I-beam

Table III. Hull Panel Geometry

DESIGN LOADS AND TEST PANEL DESIGN

A comparison of the various applicable classification rules indicated a similarity in the hull design pressures [6]. A large number of Australian built passenger catamarans are classed using the DNV rules. The test panel design was checked using the DNV rules. As shown in Table IV, the proposed panel geometry, thickness, and structural allowables satisfies the appropriate DNV rules.

DEVELOPMENT OF PREDICTIVE COMPUTER ANALYSIS OF HULL STRUCTURE PANEL

The problem addressed was how the panel could be designed to have adequate strength and minimum cost. The cost savings would be realized in terms of:

DNV Rule [4]	Item	Required	Actual
5. B 101	Plating thickness	6.19 mm (0.244 in)	7.94 mm (0.3125 in)
5. B 202	Plating thickness	6.22 mm (0.245 in)	7.94 mm (0.3125 in)
5. B 302	Plating thickness	5.28 mm (0.208 in)	7.94 mm (0.3125 in)
5. C 101	Long. stiffener section modulus	24.9 cm^3 (1.52 in^3)	27.5 cm^3 (1.68 in^3)
5. C 201	Long. stiffener section modulus	18.1 cm^3 (1.104 in^3)	27.5 cm^3 (1.68 in^3)

Table IV. DNV rule check of panel design.

1) Reduction in material and welding,
2) Reduction in hull weight,
3) Reduction in production man-hours.

To address this problem, a joint university-industry research project was initiated under the support of GCRMTC. This study is in three parts:

Part I Design of aluminum test panel,
Part II FEM analysis of test panel and comparison with Part III results to improve predictive load, elongation, and stress prediction capability,
Part III Manufacture of structural test system and physical tests of aluminum test panel.

Parts I, II, and III were performed concurrently. For example, the panel design was developed in conjunction with the design of the structural tester [7].

The test panel was sized to enable a valid comparison of the present results with the FE analyses. Earlier tests performed by

Clarkson [8] using 3 ft x 3 ft and 4 ft x 3 ft steel hull panel grillages showed the section of a 5 ft x 15 ft panel would be more than adequate for the present analysis. This opens the possibility of studying both the structural response as well as the fatigue strength of the welds.

Physical testing of the panel was performed using a structural test system. Here the test panel is mounted within the structural test system as shown in Figure 3. Multiple hydraulic actuators are used to simulate the design pressure loading. Load, strain, and deflection measurements are recorded at various locations on the panel. Table V summarizes the location of load, deflection, and strain data recorded.

The actuator loads were applied slowly up to a total of 6000 lbs. Repeated tests showed a maximum deflection of 0.071 inch at this 6000 lb loading. This compares well with the 0.084 inch mid-area deflection

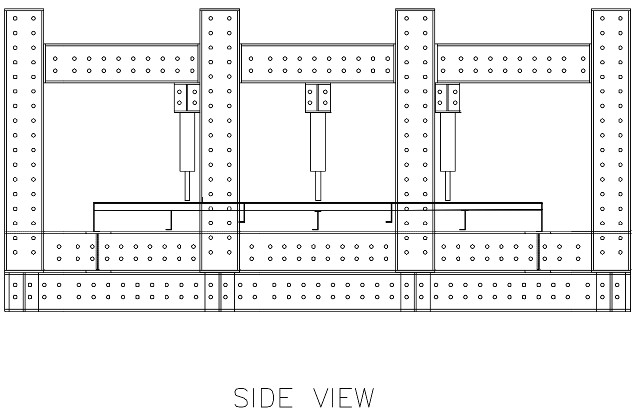

Figure 3. Panel in Test Frame

Quantity	Measurement	Location
2	Deflection	Center longitudinal
1	Deflection	Center fixed transverse
1	Deflection	Center floating transverse
2	Strain (rosette)	Shell plating
4	Strain gage	Center longitudinal
1	Strain gage	Center fixed transverse
1	Strain gage	Center floating transverse

Table V. Location of deflection and strain gages.

predicted by the finite element model. The small difference in results may be due to several factors: 1) boundary conditions around the panel edges, not acting as knife edge supports, 2) differences in the test panel geometry, and 3) thickness variations between the computer model and the test specimen.

Strain gage data were continuously recorded during the loading cycle and an additional test was performed to check for repeatability of results. The applied load and resulting strain for these tests are shown in Figure 4, along with the corresponding finite element predictions. The strain data shown is the average longitudinal strain as read from four gages. Differences between predicted and experimental results are due to a combination of factors. These include differences in actual and modeled boundary conditions, material and geometry imperfections, and model discretization.

The tests showed the validity of the finite element results in predicting the elastic load response of the panel with floating frames. This provided the basis for the optimization study and follow-on tests with a uniform pressure loading. The uniform pressure loading will be performed by evacuating the panel back using a

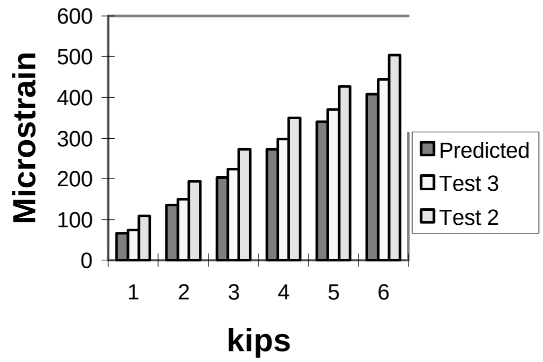

Figure 4. Comparison of Test Data and Finite Element Prediction.

vacuum pump giving,

$$P_{load} = P_{back} - 14.7 \text{ psi.} \tag{1}$$

These results with the uniform test pressure will be compared to the equivalent loads obtained with the test frame actuators.

FINITE ELEMENT ANALYSIS OF THE TEST PANEL

Finite element analysis of the stiffened plate was performed using the ANSYS® general purpose finite element code. To model the base plate, ANSYS Shell63 quadrilateral elements were used. This element has both bending and membrane capabilities along with six degrees of freedom at each node namely, Ux, Uy, Uz, θx, θy, and θz. The element Beam44, a three dimensional elastic beam element, was used to model the longitudinal and transverse stiffeners. This element also has three translational and three rotational degrees of freedom. A total of 1464 elements were used to model the plated structure. Progressively finer meshes were evaluated until the results converged.

Results of the finite element analyses are shown in Figure 5. Boundary conditions for the analysis were simply supported for the two longitudinal edges which represent longitudinal girders and fixed conditions along the transverse edges to represent transverse bulkheads. Figure 5 is a plot of the out-of-plane displacement field *w*, for the stiffened panel resisting uniform pressures of 69 KPa (10 psi) and 103 KPa (15 psi). As shown in the

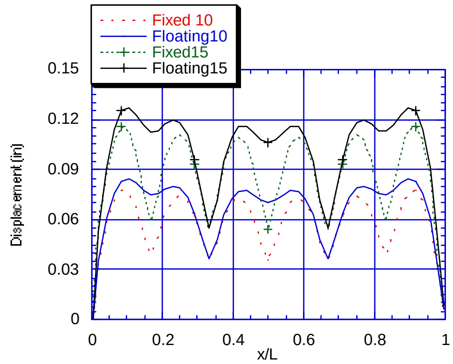

Figure 5. Finite element results of uniform pressure loading.

figure, the maximum displacement occurs with the floating frame system, and has a value of 3.35 mm (0.132 inch).

PANEL OPTIMIZATION

From the standpoint of ship production, it is important before production planning to insure that the items can be produced effectively with minimum cost materials. For high speed craft, the minimization of as-built weight is critical to achieving good performance. This can be accomplished by re-examining the structure and performing an optimization. The optimization was performed using the optimization scheme, HULLOPT.

An optimization scheme, HULLOPT, has been developed to focus on the design of lightweight/high strength hull panels. These stiffened panels will be used in the modular construction of the next generation high speed crew boats. The purpose of HULLOPT is to examine the stiffened panel behavior with different structural elements and panel thickness, in order to determine an optimum structure.

Optimization of the stiffened panel is formulated as a mathematical optimization problem. This is generally written as,

$$\text{minimize: } z = f(X) \qquad (2)$$

$$\text{subject to: } g_i(x) \le \bar{g}_i \qquad i = 1, \ldots, m \qquad (3)$$

$$x_j^{LB} \le x_j \le x_j^{UB} \qquad j = 1, \ldots, n \qquad (4)$$

where f(X) is the objective function to be minimized, $g_i(x)$ are the m constraints, along with their limits, $\bar{g}_i$. The set of n design variables are given by x_j, with the lower and upper bounds of the design variables given by x_j^{LB}, and x_j^{UB}, respectively.

The objective function for the case of stiffened panels could be to minimize weight, material and labor costs, or a combination of the two. Such a combination would consider minimizing weight in order to increase the load carrying capacity of the vessel, and hence offset greater cargo capacity with initial higher construction costs. In the sample problem solved in this paper, weight is the critical factor in this design, therefore minimum panel weight is the chosen objective function.

Behavioral inequality constraints are represented in the formulation. These constraints provide limitations on behavioral quantities such as stresses and displacements. In the sample problem that follows, the constraints follow the DNV code for aluminum high speed vessels. These constraints include:

1. minimum plating thickness,
2. minimum section modulus for longitudinal and transverse stiffeners,
3. minimum shear area for longitudinal and transverse stiffeners,
4. maximum allowable buckling stress to prevent web and flange buckling, and
5. maximum allowable local and bending von Mises equivalent stresses for plating and stiffeners.

Two additional geometric constraints were imposed on the optimization problem. The first geometric constraint is that there must be equal spacing between longitudinal and transverse stiffeners. The second constraint requires that the transverse frames alternate between fixed and floating members.

Design variables are the quantities to be determined during an optimization routine. Design variables may be dependent or independent variables that describe the problem to be optimized. For the stiffened plate, six independent design variables are used; plating thickness, longitudinal section modulus, fixed frame section modulus, floating frame section modulus, longitudinal stiffener spacing, and transverse stiffener spacing.

Input to the optimization is the initial panel geometry, thickness and stiffener size. For this analysis, overall plate geometry in terms of length and width, remained constant. Figure 2 shows the stiffened plate with alternating “floating” transverse frames. Plate geometry is given in Table III. The initial design featured a plate thickness of .794 cm (.3125 in), four 7.62 cm (3” x 1.96 lb/ft) extruded Al I-beams for longitudinal stiffeners, and five 17.78 cm (7” x 5.8 lb/ft) extruded Al I-beams for transverse stiffeners. Equal stiffener spacing was used throughout the plate, with a longitudinal spacing of .3048 m (12 in), and a transverse frame spacing of .762 m (30 in). The weight of this panel is 347 kg (765 lb).

In order to determine the sensitivity of the objective function to the design variables, the gradient of the objective function was calculated at the optimum design point. Figure 6 shows the change in objective function versus a plus or minus 1% change in the design variables. In this figure, ‘Thick’ refers to the plating thickness, ‘Iyyt’ and ‘Iyyl’ refer to the moment of inertia in the transverse and longitudinal directions, respectively. As can be seen from the figure, the thickness design variable has the greatest effect on the objective function.

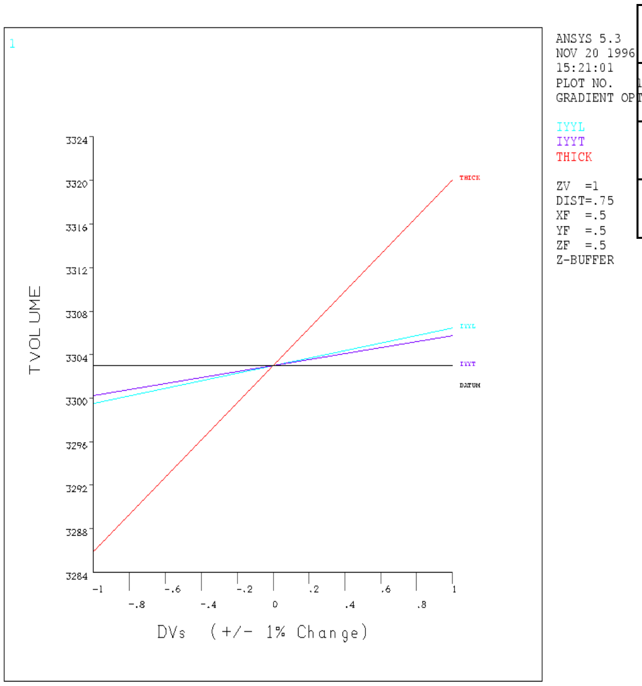

Figure 6. Gradient of design variables.

The optimization procedure was performed and results were obtained using continuous design variables. However, due to the expense of using non-standard sizes for plating and stiffeners, the optimum sizes were increased to the nearest standard size. Results from the optimization analysis are given in Table VI. In this case, the optimized design varies from the original design in terms of plating thickness, longitudinal stiffener size and spacing, and transverse stiffener size. The final design features a rolled plating thickness of .635 cm (.25 in), which is a standard size. This thinner plating required the use of an additional, yet slightly smaller, longitudinal stiffener. The longitudinal stiffener requirement may be met by the use of five Aluminum Association extruded standard I-beams 7.62 cm (3" x 1.64 lb/ft), with a section modulus of 24.42 cm^3 (1.49 in^3) [9]. Keeping a constant width required a longitudinal spacing of .254 m (10 in). In terms of the transverse stiffeners, the optimized plate retains the same number of fixed and floating frames, and retains the same stiffener size for the floating frames. However, the fixed transverse frame size may be reduced to a 12.7 cm (5" x 3.7 lb/ft) extruded aluminum standard I-beam. The weight of the optimized panel is 294 kg (648 lb), resulting in a weight savings of approximately 15%.

Description	Value
Plating material	Aluminum 5086-H116
Stiffener material	Aluminum 5086-H111
Panel length	4.572 m (15 ft)
Panel width	1.829 m (6 ft)
Plate thickness	.635 cm (.25 in)
Longitudinal stiffeners	5 - 7.62 cm (3" x 1.64 lb/ft) Al I-beam
Span between longitudinal stiffeners	.254 m (10 in)
Span between transverse stiffeners	.762 m (30 in)
Transverse floating stiffeners	3 - 17.78 cm (7" x 5.8 lb/ft) Al I-beam
Transverse stiffeners	2 - 12.7 cm (5" x 3.7 lb/ft) Al I-beam

Table VI. Optimized Panel Geometry

While obtaining an optimum hull design based on weight is the objective, the cost to produce such a hull panel cannot be ignored. Therefore, a cost analysis that considers the change in cost to produce the initial design versus the optimum design was carried out. The variable cost required to produce the optimum design is written in terms of an incremental cost equivalent relative weight (iCERW) given by [10] as,

$$\text{iCERW} = \Delta\text{material weight} + K^*\Delta\text{man-hours, (kg)}$$

where K is the ratio of the labor cost per hour to the cost per kilogram of aluminum [11]. In this case, a labor rate of $50/hr was used [12] along with a material cost of $4.40/kg. The additional longitudinal stiffener required for the optimum design, demands additional labor in terms of marking, positioning, aligning, fit and tack, and fillet welding along the stiffener length. An estimated two additional man-hours are required for this task. Given these estimates, the iCERW is -30.2 kg, indicating that the decrease in material weight offsets the increase in required man-hours.

The results indicate that optimization programs of this type can be a valuable tool that can be used at both the preliminary and contract design stage. Parametric studies performed through this study were essential in order to realize a cost effective lightweight aluminum hull structure.

Future enhancements will include stiffener and plate combinations that are evaluated in terms of both structural performance and overall cost. Other enhancements will include a sensitivity study of the various design and fabrication parameters on the overall cost.

CONCLUSIONS

This paper has presented the results of a design study for a cost effective, light weight, high strength aluminum hull panel. The hull panel was designed for panel line production and modular construction. It features the use of aluminum extrusions and alternating floating transverse frames to reduce production costs and minimize material weight.

In order to achieve these results, a 5 ft x 15 ft aluminum panel with alternate floating frames was tested in the UNO structural tester. The results were then compared with predictions made using the finite element method. The main conclusions of this study are:

1) the calculated deflection is slightly larger than the experimental measurements,
2) the calculated strains in the grillage are slightly lower than the

experimentally measured strains for the same loading, and

3) the calculated results show that the floating frame can meet the required loads.

The introduction of the HULLOPT procedure resulted in a systematic procedure to minimize the frame weight. This was accomplished by a parametric analysis based on available aluminum extrusions. The HULLOPT technique presented provides an effective method for optimizing the design of stiffened plates. The main conclusions of the optimization study are:

4) using the HULLOPT procedure and selection of available extrusions resulted in a 15% reduction in the panel weight, and
5) based on the incremental cost equivalent relative weight (iCERW), it can be shown that the reduction in weight offsets the increase in production man-hours, resulting in a net savings.

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A Computer-Aided Process For Assessing The Ability Of Shipyards To Use Technological Innovation

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ABSTRACT

This paper details a prototype personal computer based organizational evaluation system that allows a shipyard to evaluate its potential for technological innovation against a composite innovative organization. The system was developed by a combination of meta-analysis of available literature, interviews, and survey of shipbuilding industry personnel. The system is designed for self use by organizational members, and produces output that serves as basis for dialogue about changes necessary to increase the innovative capacity of a shipbuilding organization. Development and use of the system is explained, and examples of output from 2 field tests is presented. Further system development plans are examined.
Keywords: Technology, Organizational Development, Evaluation, Computer

INTRODUCTION

Organizations generally exploit the advantages of new technologies by adapting those technologies to fit their current organizational structure and strategies. This process in most organizations occurs as short periods of intensive, turbulent change, followed by longer periods of relative calm as the benefits from the change are absorbed by the organization [1]. This is a normal occurrence during the period of technological discontinuity that occurs as a process or market shifts to a newer technology. The United States shipbuilding industry, faced with the loss of the United States Navy as its prime customer, appears to have little experience with those areas of technology transfer that are necessary to maintain competitiveness in a multiple customer environment [2,3].

The research reported in this paper had two purposes. The first purpose was to determine the general ability of shipbuilding firms to use technological innovation to enhance their ability to compete in the emerging global, multiple customer environment. The second purpose was to report on a software-based system that helps increase that ability to compete by measuring the ability to innovate within an organization and suggests ways to improve it.

LITERATURE REVIEW

An assessment on what works and what does not work with regard to innovation in the shipbuilding industry was accomplished by conducting a literature review, interviews in shipyards with personnel responsible for technological innovation, and a random industry survey. Previous research in technology transfer within the shipbuilding industry supports the idea that, in general, the process of technology transfer is poorly implemented in many shipbuilding companies [2,4]. Many shipbuilding industry leaders point out that technology transfer is often identified as a highly desirable objective, but it is most difficult to obtain and the technology transfer process generally does not work as well as most participants desire [2].

Shipbuilding firms, like many organizations, are in the midst of a paradigm shift from relatively stable markets, based on the application of electromechanical tools to a customer-responsive world of continual innovation based on “technoservices” that require organizations to use technology in rapidly changing ways to satisfy multiple customers [5,6]. Organizations that are successful under this new

paradigm have many characteristics of what are known as learning organizations, i.e., organizations that have mechanisms in place to continually question and change the accepted practices of the organization, whether it be technology or management method [7,10].

One of the primary components of a learning organization is the mechanism it uses to learn from the experiences of other organizations or the results of its own actions. These mechanisms were examined as potential tools to enable shipbuilding firms to more easily assimilate what has worked in other organizations. However, the transfer of these successful mechanisms is often complicated when the root technology has a military use. Often, the technology transfer process is much more complex in the case of the so-called "dual-use" technologies, where a judgment about the threat a technology may pose to national security must be incorporated into the technology transfer decision process. Since the prevailing view is that it is better to err on the side of caution, often such dual-use technologies, while having appealing commercial applications, are restricted from utilization by bureaucratic methods that assume "it is better to be safe than sorry" [8]. This problem clearly is a deterrent to shipbuilders whose primary experience and expertise is in military systems and who wish to shift that expertise to commercial ships.

The existing literature clearly indicates the importance of shipyard executives in the process of using innovation as a competitive advantage factor. It is probably best expressed in the seminal paper in the *Journal of Ship Production* by James Rogness (1992) in which he concludes:

> "The problem is that, despite all that has been considered and tried, results have been disappointing, at best. No shipyard has been able to break out of the pack and lead the way to international competitive stature. What more is needed? What more can be tried? The answer to these questions is not comforting. No procedure, tool, or program, in and of itself, is capable of boosting U.S. shipbuilding productivity into international competitive stature. Very little improvement is possible until shipyard executives finally realize that the most powerful productivity constraints in U.S. shipbuilding exist in the form of destructive organizational policies which only they can change."

This assessment, as well as much of the other literature, tends to confirm the assumption that change management skills are a necessary factor in improving the ability of shipyards to use technological innovation to become more competitive in a global economy. Thus, the research reported in this paper approaches technology transfer as a change management problem, rather than a purely technical problem.

INDUSTRY SURVEY

While the literature provided an initial set of hypotheses about the technological innovation process in shipbuilding firms, confirmation for these hypotheses was based on information obtained from shipbuilding personnel, naval architects and marine engineers. A series of interviews with various shipyards, both large and small, and consultants to the shipyards, were conducted along with attendance at shipbuilding conferences and seminars. In addition, a major effort was initiated to survey as many U.S. shipyards as possible.

The list of potential respondents was developed by random selection from a list of all shipbuilding firms obtained from the *Society of Naval Architects and Marine Engineers* (1995). From this list, companies were selected that had identifiable personnel, such as chief engineers, technology managers, and so forth, to whom the survey could be directed. From this refined list, a random sample of 150 firms was developed. A snowball technique was then used to provide the actual sample for the study [9]. This technique was used in an attempt to overcome one of the historic problems in survey research in shipbuilding firms, that of poor response. Most researchers who study the shipbuilding industry report very poor response rates, usually about 5-6%. Obviously, this is a threat to generalizability of results.

The snowball technique used in this study consisted of identifying a primary respondent by name at each of 150 shipbuilding firms from a randomly selected list as described above. If a primary respondent name could not be determined for the firm, the firm name was discarded and a new firm randomly selected to replace the discarded firm. Each primary respondent was mailed four questionnaires along with detailed instructions to pass the other three questionnaires to other people engaged in the technology transfer process within the shipbuilding firm. Thus, a total of 600 questionnaires were mailed to 150 randomly selected firms. A second mailing of the questionnaire to non-respondents was made in two months. An invisible coding scheme was used on the questionnaires to provide a method to determine which firms needed follow-up for the second mailing. Otherwise, the replies were kept strictly anonymous, in

an attempt to increase response rate. This procedure yielded 102 usable responses, as determined by completeness of response and self-reported involvement in the technology transfer process.

The questionnaire was developed from past research in innovation and technology transfer, after initial interviews with technology transfer personnel at multiple shipbuilding firms [7,10,11,12,13,14]. This step was necessary to adapt standard questions to the unique culture of shipbuilding. The questionnaire consisted of 21 multi-item area questions and 7 open-response questions designed to determine individual perceptions about the technology transfer process within the respondent's shipbuilding firm. Specific question areas were: (1) the structure and industry sector of the firm; (2) level of success; (3) reward systems used; (4) influences on the technology transfer and innovation process; (5) the role in the innovation process played by the respondent, and (6) several open-ended questions designed to let the respondent describe successful and unsuccessful attempts at innovation within their firm. In addition, there were several other areas important to innovation/technology transfer interaction that were measured by single questions with multiple responses or ranking criteria. A complete version of the questionnaire is available from the authors.

SURVEY RESULTS

Some selected survey results are indicated below:

- 72% of respondents think they are performing better than their competition.
- Most respondents fail more than they succeed at bringing new innovations into their company.
- Only 2% of responding companies have specific reward systems that implicitly reward technological innovation.
- The most important considerations when adopting a new technology are:
  - Customer requirements,
  - The CEO wants the technology, and
  - Others in the industry are using.
- The primary decision criteria used to decide which innovations to use are:
  - Faith innovation will work, and
  - It is a primary customer decision feature.
- Very few firms actually used objective criteria for decision-making about technology, but many have a system that is used to justify decisions once they are made.
- Reasons for technological failure (in rank order)`
  - Lack of management commitment
  - No cross-organization input
  - No market reason for innovation
  - Too expensive to be competitive
  - Software unfriendly
  - Ad hoc procedures
  - Culture that rewards heroics
  - Not a core market for company.

Overall, the results of the survey confirmed that management was indeed extremely important in the technology adaptation process in the shipbuilding industry. This clearly echoed the conclusions of Rogness mentioned previously. In addition, the tone of the replies indicated an industry in denial. With the United States shipbuilding industry constructing less than 1% of the global newbuilding market, arguably the 72% who perceive that they are doing better than the competition are [2,15]:

- Either in denial of international competition, or
- Do not understand that the U.S. shipbuilding industry is moving from a single customer (the United States Navy) to multiple customers, mostly in the commercial sector.

This type of attitude is not uncommon among personnel in industries which have been relatively stable for many years and which are beginning to undergo dramatic changes. The steel industry, airlines, banking, and the telephone industry are past examples of industries where this behavior has been observed [16,17,18]. The problem is, that when in this situation, many companies still refer to their historical successes and fail to realize that those methods and procedures are no longer applicable.

DETERMINATION OF SYSTEM

The objective of this project was to produce a system which enhances the capability of shipbuilders to utilize new technologies to increase their competitiveness in a global market. The system was to be usable by *all* shipbuilders, which greatly complicated the development process. However, the funding organization specified that the objectives of the project were to "increase the international competitive ability of United States based shipyards." Thus, the system had to be responsive to the individual company situation across a wide variety of organizations. Given this constraint, the type of system and method used to reach the objective was changed from that initially visualized as a result of the literature review, the industry survey, and

interviews. In essence, it became apparent that the system was expected to be more useful if it enhanced the shipbuilder's ability to *recognize the need for change* rather than provide prescriptive directions on how to change. A "self-help" model which could assist shipbuilders in doing a better self-assessment of their innovative potential and capabilities would be much more useful than an expert system model which assisted shipbuilders in evaluating the probability of success of potential innovations.

The outcome of this phase of the research process was to develop a technology transfer model which could be used to benchmark each shipbuilding company against a composite innovative company. As in most good bench-marking efforts, the composite innovative company is not necessarily based on the most innovative shipbuilding companies, but rather those companies which are world class in the function being benchmarked [19]. The results of this approach gives two important parameters for self-assessment. The first is alignment (both internal and with the composite company) which can be critical information with the emerging emphasis on teams and effectiveness.

The second parameter is the relative position of the shipbuilding company with the composite company, which gives information on areas that may need improving. Perhaps the most significant feature of the system is the self-help feature. The major benefit of the system is the dialogue framework that it develops. Through the use a facilitator, questions such as "Why do we score so low in the management section?" or "Why do we have so little agreement (alignment) on technology issues ?" are explored by those who are responsible for technological innovation in the company. Thus, by increasing communication and group effectiveness, the system increases the capacity for innovation within a company [7,12,14]. The system develops no prescriptive answers, but rather becomes a means of stimulating serious questions about individuals and company policies in a non-threatening environment. Use of the model should be most effective when used by upper management teams, but it is designed to be used at any level and should prove to be particularly useful in reviewing alignment of various internal groups and teams.

In this dynamic world in which the shipbuilding industry has found itself, some positive changes have already been noted since the survey was completed in January of 1996. In particular, there has been increased interest in changing the business management model for many shipyards. This is especially true with regard to teams and concurrent engineering. This change may be driven, in part, by the United States Navy, because of its teaming requirements in the bid process for major new projects, i.e., the LPD-17 project.

In addition, topics such as incentive pay for innovation and productivity, process improvement and change management are becoming more common in articles in shipbuilding industry journals and in the National Shipbuilding Research Program. Despite these positive changes, which were generally not reflected in the responses, it is still believed that a self-help innovation system which develops internal dialogue is the most overall useful tool to increase technological innovation, within the immediate future, in shipbuilding companies.

DEVELOPMENT OF THE MODEL

The system is based on a meta-analysis of existing literature on technology transfer and innovation as well as the results of the shipbuilding industry survey and interviews with participants in the innovation process. The model is shown in Figure 1.

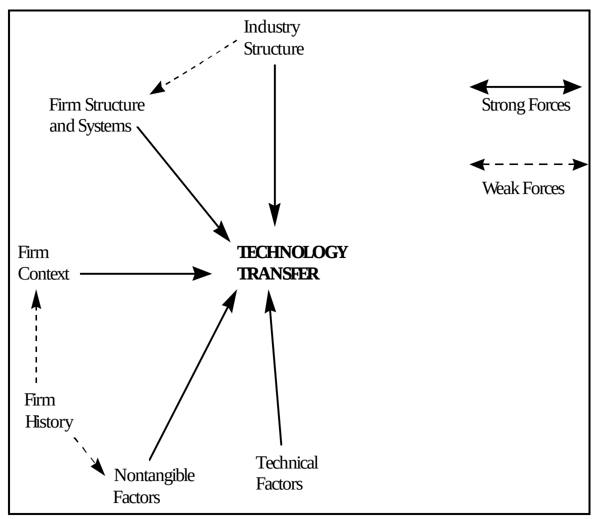

Figure 1, Influences on technology transfer process in shipbuilding companies.

Table 1 shows the elements of each of the primary influences in figure 1. The model elements in table 1 were used to develop question areas that measure the degree of innovation capacity inherent in an individual shipbuilding company or subgroup.
These elements in most studies were found to be responsible for significant portions of the explainable variation in innovative capacity between different companies or groups [7,8,10,12,14,20,21].

INDUSTRY STRUCTURE Strategic Group Competitive Analysis Market	FIRM CONTEXT Performance Perceptions Decision Domain Target Sponsors Agent Size
FIRM STRUCTURE Reward Systems Top Management Culture Organizational Structure Accounting Systems	FIRM HISTORY Traditional Markets Traditional Skills Perceived Strengths
TECHNICAL FACTORS Type of technology Relatedness Congruence	NONTANGIBLE FACTORS Non-Quantifiable Factors Underestimating Cost Underestimating Benefit Risk

Table 1, Elements of Technology Innovation Influence Model

INNOVATION QUOTIENT

The model of influences was used as a framework to develop a question-based software system designed to be used by individuals within a shipbuilding company. The individual answers users provide are then aggregated in a post-processing module that allows graphic comparisons of various areas that show the overall innovation potential of the group or individual being evaluated. The aggregate answers can also be used to suggest areas for improvement that will increase the technological innovative capability of the company. The measure of potential for innovation has been termed the "Innovation Quotient", or **IQ**, in an effort to give the system a short, easily recognizable name.

While the soundness of the system is based on the current information available on innovative companies, the usefulness of the model is also directly affected by the format of the software used in the self-evaluation portion of the system. The software will continue to be improved as more user-friendly input software and more beta-test user response is gathered. A short description of the existing software will be given here

After working with C++ as a language for the initial proof of concept software, it was decided that it would be more effective to use a commercially available software authoring package. Since many of the procedures needed in the system have aspects similar to data bases, we decided to use *Microsoft FoxPro version 3.0* as a development system**.** This product provides both software development and the ability through the licensing agreement provided with the *FoxPro* authoring package to distribute the finished product to interested parties in the shipbuilding industry without having to pay additional royalties for use. An important part of this project is to distribute the end product to as wide an audience in the shipbuilding industry as is possible. The software developed with the *FoxPro* system runs on any Windows® or Windows 95® equipped personal computer. During the test period the software was also successfully run on a Macintosh computer.

SYSTEM TESTING

In actual use, the software portion of the system is used by the various stakeholders in the shipyard innovation process. The software captures the perceptions of the stakeholders through recording in a database file the answers the participants in the process give to the questions asked in the software. The answers the participants in the process give are used for two purposes. First, the answers of the respondents are compared to a set of answers that would be the norm for an innovative company. This is done through a Likert form additive scale that allows an overall measure of innovative capacity and also allows evaluation of innovative capacity in relation to a composite of innovative companies in several sub-areas that are components of the model.

Second, the answers are compared to each other so that the degree of correlation between each of the participants can be determined. By forcing each of the participants in the innovation process to specify their perceptions about important elements of the process or technical area being considered, potential problem areas can be identified and dealt with in a more efficient and effective manner, leading to an improved technology transfer process. The software displays the information both as text and in graphical format, thus facilitating comparison between and among stakeholders in the innovation process.

The first group to utilize the beta version of the software was selected from a major shipbuilder, whose expertise is mainly in building combatant vessels. A subgroup of that shipyard was a team whose responsibilities include evaluating new innovations for possible implementation.

After some introductory remarks on the purpose of the model, six members of the group utilized the software. The recorded answers were analyzed and in a follow-up session the results were

discussed with the group. Examples of two graphic outputs for this group are presented in appendix 1. Topics that were explored with the group as a result of the graphic results were:

- What was the source of the relatively low scores in the firm structure construct?
- Why were there large variations in scores in the technical construct?
- Was the difference in the profile shapes significant in regard to decisions made about technologies?

In addition, many other areas were explored that discussion of the results facilitated. The end result was that the participant agreed that there were some firm-level structural problems that upper management needed to remedy and there was also a need for increased communication in certain areas within the R&D organization. The comments of the participants was generally favorable, with most criticism directed at improvements that needed to be made in the software user interface.

Figure 5 illustrates the results obtained from the upper management group of a marine telecommunications company. While this is a different industry from what the system was originally designed, we wanted to test the system with a successful organization that we knew was in a dynamic competitive industry. As you can see, the results are different in 2 ways. The first difference is the degree of convergence shown in the group innovation profile. Even though there were 11 participants with varying job titles, the degree of convergence is higher than the shipbuilding company sample. This profile is what we expected of a successful company in a competitive industry. While it is possible to debate whether groupthink could possibly lead to the same profile, our initial analysis supports the view that there was increased ability to deal with technological innovation in this company.

The overall innovation quotient (IQ) for the telecommunications group, shown in Figure 4 , is also different from the IQ for the R&D group, shown in figure 3. The overall IQ score is indicative of the comparison with a composite innovative company. Thus, factors in the industry structure variable, as in the telecommunications industry, could mean that a company could have a lower innovation score because of variables such as size and number of competitors. While most of the factor scores are somewhat higher for the telecommunication group, the industry structure factor is a lower score. This is consistent with what would be expected, given the difference in size and competitive market for the two companies.

The face validity of the system and user comments have been very positive to date. Further testing, reliability analysis, and question improvement are expected to be accomplished in the follow on project.

FUTURE POTENTIAL

The results of the shipbuilding test group have been encouraging**.** The **Innovation Quotient** software clearly was successful in creating meaningful dialogue and suggestions for ways in which the innovation process could be improved in the test group.

In December, 1996, the system and test results were presented to a larger group of shipbuilding industry representatives. The presentation included a demonstration, question and answer session, and feedback from the participants on the anticipated usefulness of the system.

Based on our test results and the additional industry feedback received from the December 1996 presentation, we propose the following as the direction for future work on the IQ system. We should first improve the self-help characteristic of the software. This will be an important step because the increasingly competitive environment of the shipbuilding industry. It is believed that the software can be developed to the point in which companies could self-administer and self-analyze the results without sharing them with outside facilitators. The ability to use outside facilitators will be retained, and the system user will have the option to make the results/review proprietary. This improvement of the self-help feature will require that the questions in the authoring section be updated as innovative practices in companies change. These continual improvements will not only involve the update of the questions, as required, but also the upgrades in software to make it more user friendly. We should then add options to the graphic output section of the post-processing module to allow more combinations and types of outputs to suit individual needs so that self-analysis is easier to accomplish. These improvements should be done by a central group in the shipbuilding industry, most likely the originators of the software concept.

The final improvement to the system is to develop an additional set of questions so the self-analysis software could be used to evaluate the team-based management potential of a company. This will require additional meta-research in order to develop a composite of key best-in-class team attributes. This teaming software would be used in a similar fashion to

the innovation software except it would be specifically applied to teams and groups in which teamwork is important. It would also be a self-help package which would result in two main outputs as in the IQ system, recommended suggestions and dialogue.

This improvement would provide two self-help packages, one on innovation and one on team based management, which should be very useful to the shipbuilding industry. The software packages would be maintained and updated by an Innovation and Team Management Center established as a subgroup of the Gulf Coast Region Maritime Technology Center in New Orleans.

In summary, the computer-aided process for assessing the ability of shipyards to use technological innovation seems to be a powerful tool for shipbuilders because of its self-analysis concept. It allows companies to take a serious look at their innovative processes, without involving an outside consultant and the corresponding risk of loss of competitive advantage. With the increased importance of integrated teams in shipbuilding, the proposed team management function of this computer-aided process should prove to make the basic IQ system even more useful.

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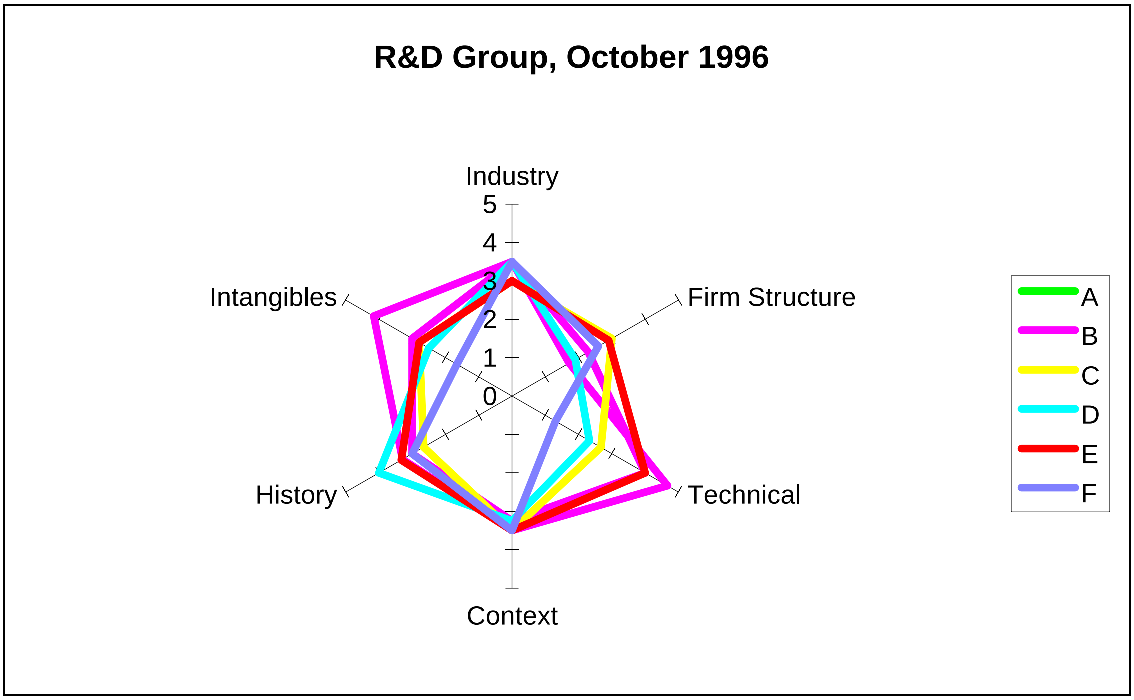

Figure 2, Group Innovation Profile, Research and Development Group

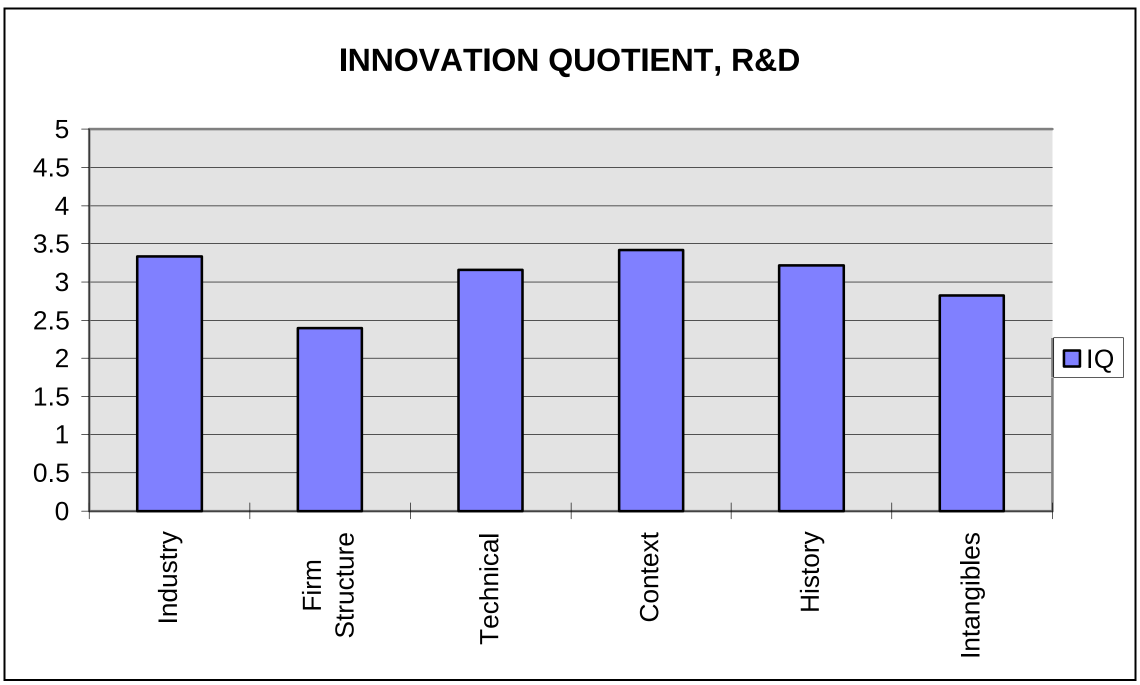

Figure 3, Overall Innovation Quotient, Research & Development Group, October 1996

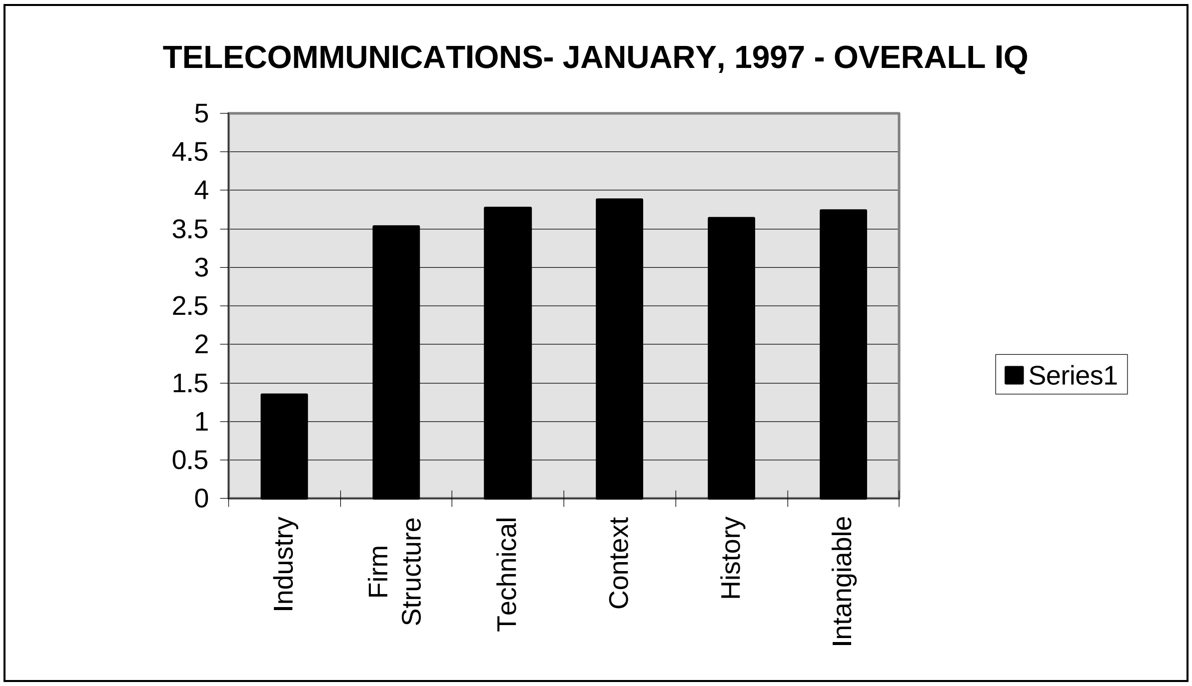

Figure 4, Overall Innovation Quotient, Telecommunications Group, January 1997

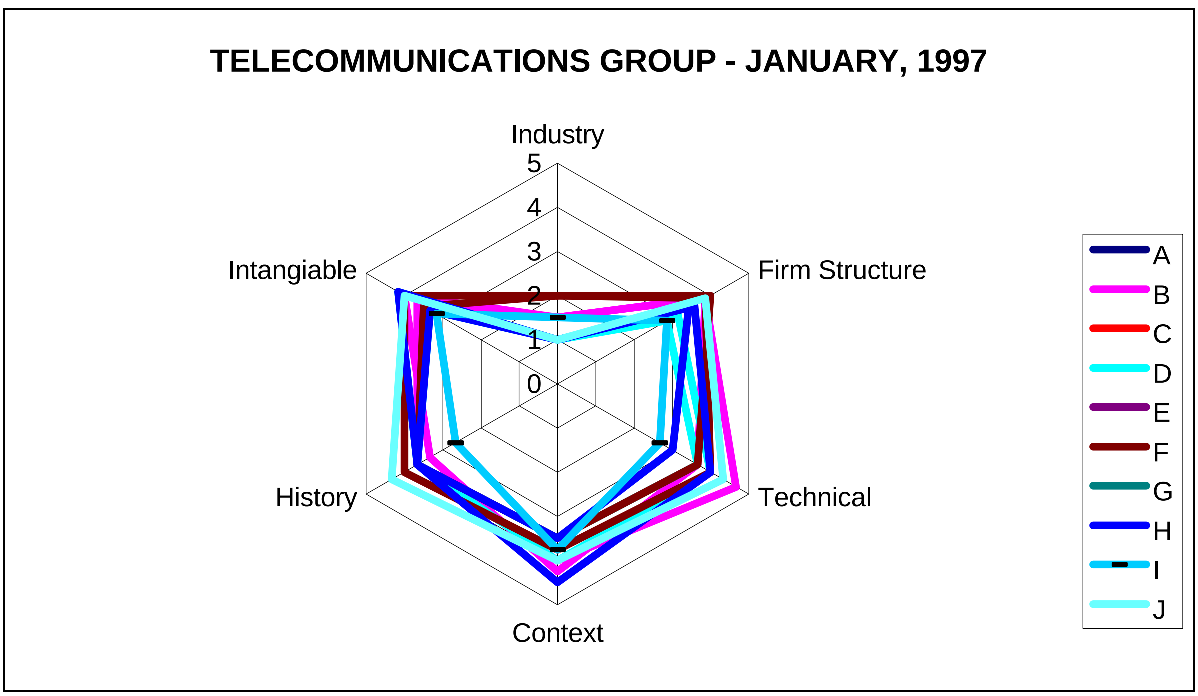

Figure 5, Group Innovation Profile, Telecommunications Group, January 1997

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A Parametric Approach To Machinery Unitization In Shipbuilding

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ABSTRACT

During the past ten years, both U.S. and foreign shipyards have developed advanced unitization concepts that include multi-level assemblies representing large vertical segments of ship machinery spaces. This paper describes a parametrically derived family of large, fully integrated standard machinery units that are applicable over a range of ship types and installed horsepower. The results include a hierarchy of standard units, the selection of standard unit sizes and interfaces, the development of parametric standards for system design, engine room arrangement and structural design, and machinery unit structural and outfitting design. Benchmarking is reported with respect to Japanese and European shipbuilding practices, and with respect to U.S. land-based industrial plant design and construction practices. The proposed unitization concept is demonstrated in a ship-specific engine room arrangement design effort. A business assessment for this unitization concept is presented which addresses its potential shipbuilding cost and schedule impacts as evaluated by three U.S. shipyards.

NOMENCLATURE

Advanced Outfit. Installation of outfit systems and components on a structural block or outfit unit prior to shipboard erection.

Block. Hull structural interim product which can be erected as a block or combined as a grand block.

ERAM. Engine Room Arrangement Model Project, part of the Navy's Mid-Term Sealift Technology Development Program.

Grand Block. Assembly of two or more structural blocks mated prior to onboard erection.

Ground Outfit. Outfit installation during on-unit and on-block outfit stages.

Grand Unit. Assembly of two or more outfit units mated prior to onboard erection.

Integrated Machinery Unit. Ship specific assembly consisting of one or several outfit systems including all mechanical and electrical components and subsystems in an area.

On-Block Outfit. Outfit installation on a structural block prior to erection onboard.

On-Unit Outfit. Outfit assembly and installation on an outfit unit prior to erection onboard.

Onboard Outfit. Outfit installation following structural block erection.

Pipe Unit. Assembly consisting of all pipe and adjacent distributed systems supported on a common hanger system.

Standard Machinery Unit. Assembly consisting of a standard structural unit, one or more system units, and all ship's distributed systems in an area. The standard machinery unit design is based upon standard unit structural and system interfaces.

Standard Structural Unit. Structural foundation and grating support for a standard machinery unit. The structural unit consists of a standard repeating structural pattern and contains framing and supports for system units and ship's distributed systems.

Structural Unit. Structural foundation and grating support for an outfit unit.

System Unit. Assembly consisting of all mechanical and electrical components making up a single subsystem on a common foundation.

INTRODUCTION

During the past two decades, U.S. shipbuilders have applied advanced outfitting techniques to ship and machinery space construction in order to achieve reductions in production cost and cycle time. While the initial application was in on-block outfit of structural blocks, this soon evolved to include on-unit outfit using system and pipe units. Even in the most successful of these initial applications, shipbuilders found that significant onboard outfit installation and test remained in complex areas such as machinery spaces.

In 1992, National Steel and Shipbuilding Company (NASSCO) implemented an innovative machinery unitization strategy on its new construction Strategic Sealift Ships that resulted in the majority of machinery space equipment, components and systems being assembled in fifteen large integrated machinery units. These ships are currently in production with significant

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Design and Production Of ANZAC Frigates For The RAN And RNZN: Progress Towards International Competitiveness

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ABSTRACT

ANZAC, the acronym of the Australian and New Zealand Army Corps, is the name given to a new class of ten frigates under construction for the Royal Australian and Royal New Zealand Navies. The prime contract was awarded in November 1989, and a separate design sub-contract was awarded concurrently. HMAS ANZAC, the first of eight ships for the Royal Australian Navy (RAN), was delivered in March 1996. HMNZS Te Kaha, the first of two ships for the Royal New Zealand Navy (RNZN), is to be delivered in March 1997.

The paper describes the collaborative process, involving the Australian Department of Defence, the New Zealand Ministry of Defence, and Defence Industry in Australia, New Zealand and overseas, for the design and production of the ships. The need to maximize the level of Australian and New Zealand industrial involvement, led to a process of international competition between prospective suppliers, and significant configuration changes from the contract design baseline. Delivery of the first ship was extended to accommodate the revised approach, and in the event only five months additional time proved necessary. Although formal acceptance of HMAS ANZAC is not due until the completion of operational test and evaluation, the contractor's sea trials have successfully demonstrated the performance exceeding the requirements and the expectations of the RAN.

The paper also describes the growing maturity of Australia's naval shipbuilding industry. It suggests some lessons learned from the project, and identifies issues important for the further development and sustainability of the industry. It advocates the need for agreed methodologies to evaluate the productivity of the various elements of the shipbuilding process, and to help ensure the establishment and maintenance of world competitive costs and quality.

NOMENCLATURE

AMECON	Australian Marine Engineering Consolidated
AMT	Australian Marine Technologies Pty. Ltd.
ANZAC	Australian and New Zealand Army Corps
ANZII	Australian and New Zealand Industry Involvement
ANZIP	Australian and New Zealand Industry Program
ASSC	ANZAC Ship Support Centre
ASTEC	Australian Science, Technology and Engineering Council
BAFO	Best and Final Offer
BAINS	Basis for Acceptance Into Naval Service
B+V	Blohm+Voss GmbH
BVA	Blohm+Voss Australia Pty. Ltd.
C^3I	Command, Control, Communications and Intelligence
CDAMS	Contract Definition and Monitoring System
CER	Australian and New Zealand Closer Economic Relations
CFI	Contractor Furnished Information
CGT	Compensated Gross Tonnage
CIPFS	Critical Item Product Function Specification
C+M	Control and Monitoring System
C/SCS	Cost/Schedule Control System
CST	Contractor's Sea Trials
CSTOR	Combat System Tactical Operational Requirement
CSTT	Combat System Tactical Trainer
DDC	Documentation Development Contract(s)
DDG	Charles F. Adams Class Destroyer
DOR	Detailed Operational Requirement
DSC	Design Sub-Contract
DT&E	Development Test and Evaluation
FFG	Oliver Hazard Perry Class Frigate
GFE	Government Furnished Equipment
HMAS	Her Majesty's Australian Ship
HMNZS	Her Majesty's New Zealand Ship
ILS	Integrated Logistic Support
IMS	Index of Materials and Services
ISO	Industrial Supplies Office
ITP	Integrated Test Package
MEKO	Multi-Purpose Combination Frigate
MOU	Memorandum Of Understanding
NSRP	National Shipbuilding Research Program
OA	Operational Availability
OT&E	Operational Test and Evaluation
PC	Prime Contract(or)
PT&E	Production Test and Evaluation
RAN	Royal Australian Navy
RAST	Recovery Assist Secure and Traverse System
RFT	Request For Tender
RNZN	Royal New Zealand Navy
SEL	Standarized Equipment List
SPS	Ship Performance Specification
SWBS	Ship Work Breakdown Structure
TDS	Transfield Defence Systems
TSC	Technical Subject Code
USN	United States Navy
VLS	Vertical Launch (Missile) System
WDS	Williamstown Development Site

INTRODUCTION

In the lead up to World War I, Australia's navy was established by purchasing warships from the United Kingdom, and by building in Australia to UK designs. Warships built during and after World War II were also to British designs until, in the early 1960's, an order was placed in the U.S. for guided missile destroyers (DDGs).

Jeremy [1] described attempts during the late 1960's and early 1970's to establish an Australian warship design capability. However, a planned Fast Combat Support Ship, and a Light Destroyer that grew to over 4200 tons, were each assessed as more expensive than overseas procurement, and plans for local build were cancelled. This experience led to a defense policy that naval acquisition should proceed on the basis of minimum technical risk and be based on an established design.

During the late 1970's and early 1980's, the Royal Australian Navy (RAN) purchased four USN FFG-7 Class frigates built by Todd Shipyards in Seattle. Two more FFG's were also ordered from Williamstown Naval Dockyard under the Australian Frigate Project.

Proposals for submarine and combat system designs based on "proven designs" were called for in 1983. The RAN became strong advocates of building its warships in Australia, and the government agreed the expected benefits would only be fully realised if the design was optimised for Australian production, and all ships of the class were locally built. It was assessed that Australian construction costs might be slightly higher than the costs of overseas procurement, but enhanced in-country support capability would more than offset this incremental cost.

The submarine construction project reduced competition to two shortlisted contenders, and the Kockums/Rockwell proposal became the basis of a contract in 1986. The design selected had a submerged displacement of more than double the largest submarine Kockums had

ever built, and a highly advanced combat system. The construction of the Collins Class submarines involved significant departures from a proven design.

In 1984, in parallel with the submarine project, the New Destroyer Project was established with the aim of selecting a design for local production. Dechaineux and Jurgens [2] described the acquisition strategy and development of the ANZAC Ship Project up to Contract Award. In the interests of risk reduction, and given early schedule pressure, a strategy was decided to seek an “existing design”, defined as a ship under contract for construction at that time. As for the submarines, it was envisaged that the new ships would be commercially built, and the Navy would not stay in the shipbuilding business.

During the 1990’s, the naval shipbuilding industry in Australia has been revitalized. HMAS ANZAC, the first of ten new frigates was successfully delivered to the RAN by Transfield Defence Systems (TDS) on 28 March 1996.

The second ANZAC Ship, HMNZS Te Kaha, is scheduled to be delivered in Australia to the Royal New Zealand Navy (RNZN) in March 1997. Follow ships are planned to be delivered at twelve month intervals in a building program that will continue until the year 2004. With a current total project cost of approximately A$ 6.059 billion (December 1996 prices and exchange rates), the ANZAC Ship Project is the largest acquisition project undertaken by the Australian Department of Defence.

Other current major naval shipbuilding projects for the RAN include the construction in Australia of submarines, minehunters and hydrographic ships. HMAS Collins, the first of six large conventional submarines was delivered by the Australian Submarine Corporation (ASC) to the RAN in July 1996. Coastal Minehunters to a design similar to the Gaeta Class developed by Intermarine of Italy are under construction by Australian Defence Industries (ADI). A contract for the design and construction of two Hydrographic Ships was also awarded in 1996 to NQEA Australia.

A factor which is critical to the future of Australia’s naval shipbuilding industry is the sustainability of demand. The current new construction program for the RAN represents a peak in domestic demand, and cannot sustain the industry in the long term. Export market opportunities are seen as vital for the industry to survive and grow. To achieve success in export markets, it is essential for Australia’s naval shipbuilding industry to be internationally competitive. This pre-supposes an understanding of what it means to be internationally competitive, and the parameters by which international competitiveness in naval shipbuilding is measured.

This paper describes the policy of the Australian Government for the development of a self-reliant defense capability, the objectives of government and industry in undertaking the design and construction of ten ANZAC frigates in Australia, the means by which the program has been implemented, and the resulting achievements. The paper also reviews some of the issues associated with the measurement of international competitiveness in naval shipbuilding, and the application of “benchmarking” to demonstrate “value for money” in defense procurement.

BACKGROUND TO PROJECT DEVELOPMENT

Cahill and Bunch [3] documented a comparative study of foreign naval acquisition, design and construction policy and practices, against the established U.S. acquisition process. The comparative study involved Canada, the U.K., France, Germany, Italy and Japan. Each of the countries described have ongoing projects involving the indigenous design of surface combatants, although in the case of Japan, the development of the Kongo Class Aegis destroyers was developed with design input from the USN DDG-51 Class destroyer program.

By comparison, the policy and practices adopted by the Australian Department of Defence have, in the past, related to the acquisition and modification of ship designs from overseas countries. The ANZAC Ship Project was based upon the selection of an “existing design” for construction in Australia, and was not conceived as a developmental project. Consequently, none of the models described by Cahill and Bunch accurately represent the acquisition process adopted by the Australian and New Zealand Governments for the ANZAC Ships.

In a paper presented to the 1990 Ship Production Symposium, Dechaineux and Jurgens [2] described the strategy adopted by the Commonwealth of Australia, in a joint project with the Crown of New Zealand, for the acquisition of ten ANZAC frigates. The paper described the ANZAC Ship Project from its inception, through the competitive selection of two alternative existing designs, the short listing of Australian shipbuilders as potential prime contractors, and the teaming arrangements between designers and builders to respond to a Documentation Development Contract (DDC) in parallel with a Request For Tender (RFT). During this process, the Dutch shipbuilding company Royal Schelde offered the "M" Frigate via a consortium called Australian Warship Systems. Blohm+Voss Australia Pty. Ltd. (BVA), a subsidiary of the German shipbuilding company Blohm+Voss AG (B+V), offered the MEKO 200 ANZ frigate design in partnership with Australian Marine Engineering Consolidated Limited (AMECON), now called Transfield Defence Systems (TDS).

Following tender evaluation, a round of Best and Final Offers (BAFO), and source selection, a prime contract was negotiated with TDS and signed on 10 November 1989 for the design and construction of ten ANZAC frigates. On the previous day, in anticipation of the prime contract award, a design sub-contract (DSC) was signed between TDS and BVA, now called Australian Marine Technologies (AMT), for the provision of the design licence and technical services for the MEKO 200 ANZ frigate design.

Steel for the first ANZAC frigate was cut on 27 March 1992, and the ship was launched on 16 September 1994. Contractor's Sea Trials were conducted in January and February 1996 and the ship was delivered to the RAN on 28 March 1996. The commissioning of HMAS ANZAC took place on 18 May 1996. Following a period of Operational Test and Evaluation (OT&E), it is expected that HMAS ANZAC will be formally accepted into naval service in mid to late 1997. It is also expected that ANZAC Ship 02 will be delivered to the RNZN in early to mid 1997, and commissioned as HMNZS Te Kaha.

PROJECT OBJECTIVES

Australian Government Objectives

According to West [4], the objectives of the Australian Government in proceeding with the ANZAC Ship Project included:

- ships for the Navy (maritime force structure considerations),
- furtherance of government industry policy (rationalization), and
- assisting New Zealand in a collaborative venture.

Ships for the Navy - Maritime Force Structure Considerations. A review of maritime force structure in 1985/86 established requirements for three generic capability levels of "Tier One" destroyers and frigates, of "Tier Two" patrol frigates, and of "Tier Three" patrol vessels, and it was decided the first need was for the patrol frigate class. The Government objectives for the ANZAC Ship Project, were defined as part of a defence review by Dibb [5], then the Director of Joint Intelligence. The review was conducted within the framework of Government policy which required self-reliance, a coherent defense strategy and an enhanced defense capability. Dibb advocated the need for a light patrol frigate to complement an essential core force of 8 to 9 destroyers (currently comprising 3 DDGs and 6 FFGs).

Furtherance of Government Industry Policy. Defense policy for industry provided a second major Government objective. In his report, Dibb [5] commented on the need for private sector involvement in defense purchasing and identified shipbuilding and repair as the next priority for reform.

As a consequence of a revised Defense policy for industry, the former government-owned Williamstown Naval Dockyard was sold in February 1988 to a consortium of three Australian engineering companies, known as the Australian Marine Engineering Corporation (AMEC). The sale included the task of completing two FFG-7 Class frigates under the Australian Frigate Project.

The company was subsequently renamed Australian Marine Engineering Consolidated Limited (AMECON) following a successful takeover of the three companies in 1988 by the Transfield Group, one of Australia's largest privately owned companies.

Defense policy for industry also includes maximizing the level of Australian and New Zealand Industry Involvement (ANZII) in defense purchasing, including naval ship acquisition projects. This policy provided a major objective for both the ANZAC Ship and Collins Submarine Projects, which were seen as opportunities to revitalise Australia's shipbuilding and heavy engineering industries.

Assisting New Zealand in a collaborative venture. Regional collaboration in defense is a priority of the Australian Government, and this policy extends to defense acquisition projects. The ANZAC Ship Project is the most ambitious collaborative project undertaken to date. In addition to promoting cooperation, joint acquisition projects offer potential economies of scale.

New Zealand Government Objectives

New Zealand's objectives in collaborating with Australia on the ANZAC Ship Project also included maritime force structure considerations, and the furtherance of government industry policy. Concurrent with Australia's need for frigates, New Zealand had a requirement to replace two Leander Class ships in the mid 1990s, and a further two after the turn of the century; effectively the replacement of the New Zealand fleet.

To formalize the collaboration between the Governments of Australia and New Zealand for the ANZAC Ship Project, an MOU was signed on 6 March 1987. Under the MOU, a supplementary agreement called the "Agreement between Australia and New Zealand concerning collaboration in the Acquisition of Surface Combatants for the RAN and RNZN" (also called the Treaty) was signed on 14 December 1989. The Treaty covers the major issues, including the management of the Joint Project, payment arrangements, industry participation, integrated logistic support, rights under the prime contract, and optional ships (11 and 12).

Under the ANZAC Ship Treaty, and consistent with another Government to Government Treaty relating to Closer Economic Relations (CER), the Australian and New Zealand defense ministers agreed to treat the industries of Australia and New Zealand as a common industrial base for the purpose of defense procurements and to treat the other's industry as it treats its own.

Industry Objectives

According to conventional business principles, the objectives of industry are simple: to stay in business and to provide a good return on the capital invested. In the early days of the ANZAC Ship Project, the prime contractor defined its objectives as being: to become an internationally viable shipbuilding and marine engineering company, to successfully complete the Australian Frigate Project; to win and successfully complete the ANZAC Ship Project; and to win export contracts for Australia, which would involve developing a full design capability.

The ANZAC Ship Project has given the prime contractor an opportunity to become a significant player in the domestic and international defense industry. This vision includes a commitment to create a sustainable "world-class" naval shipbuilding capability, and to develop the Australian and New Zealand industrial capability.

PROJECT IMPLEMENTATION

Program Management Overview

The scope of the project includes the acquisition of ten ANZAC ships and three shore facilities, as the major deliverables. Of the ten ships ordered, eight are for the RAN and two (ships 02 and 04) are for the RNZN. The contract includes an option for a further two ships for New Zealand (ships 11 and 12). The three shore facilities comprise the ANZAC Ship Support Centre (ASSC) located at Williamstown, and two Combat System Tactical Trainers; one located at HMAS Watson in Australia and one located at HMNZS Tamaki in New Zealand. The project also involves the development of an integrated logistic support (ILS) package, including training.

Consequently, the range of capabilities required to fulfil the scope of the project includes expertise in project management, systems engineering, software engineering, and integrated logistic support, in addition to naval ship design and construction skills.

An overview of the top level management arrangements for the project is provided in Figure 1.

Contract Management

Contracting Arrangements. The prime contract between the Commonwealth of Australia and the builder takes the form of a fixed priced contract worth $A 4.206 billion (in December 1996 prices), which includes price variation for escalation and is in multiple currencies.

A feature of the contracting strategy was to minimize the number of items supplied as Government Furnished Equipment (GFE) to only those items which could not be supplied cost-effectively by the prime contractor, such as the missile launcher, gun and cryptographic equipment. In accordance with the project objectives, the prime contract requires a high level of Australian and New Zealand Industry Involvement (ANZII). The prime contract also requires the

establishment by the prime contractor of a Cost/Schedule Control System, and a Quality System to ISO 9001.

The prime contractor has overall responsibility for project implementation. This includes the design of the ships and shore facilities, procurement of systems, equipment and materials, construction of ships and shore facilities, set-to-work, test and evaluation, and provision of an initial ILS package. In specialist areas, selected responsibilities, together with the relevant contractual provisions, flow down in "back-to-back" arrangements to sub-contractors.

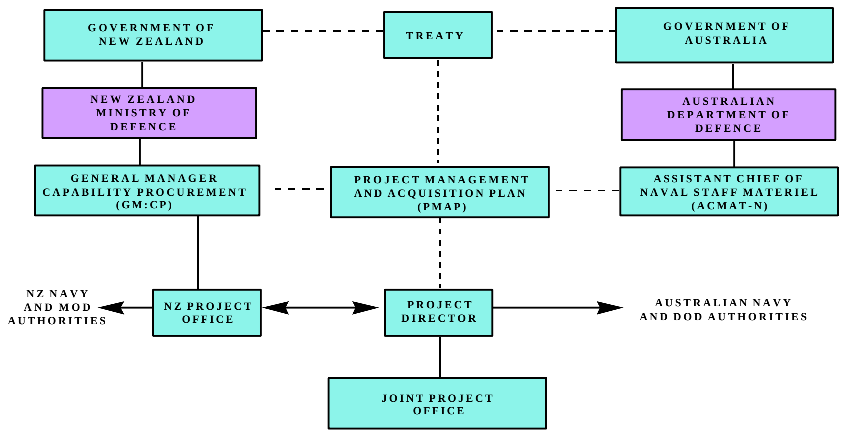

Figure 1. Top Level Management Arrangements

The principal sub-contractors include:

- Australian Marine Technologies Pty. Ltd. for ship design;
- CelsiusTech Australia Pty. Ltd. for Command and Control system design and integration;
- Computer Sciences Corporation Australia for Combat System simulation software development;
- Scientific Management Associates Pty. Ltd. for ILS management, including training;
- Siemens Industries Limited for Electrical Systems supply and system integration; and
- Stanilite (now a part of Australian Defence Industries Pty. Ltd.) for Communications Systems supply and system integration.

Cost/Schedule Control System. The prime contract includes a requirement for a Cost Schedule Control System (C/SCS) to be established by the prime contractor as an internal project management tool. The system implemented by the prime contractor was subject to formal review and audit by the Department of Defence. Formal accreditation was granted on 25 October 1993. Under the prime contract, the project authority does not have access to cost data held in the system.

Contract Definition and Monitoring System. The prime contract is a fixed price contract and financial progress is reported against priced planning and work packages rather than costs incurred. For this purpose, a Contract Definition and Monitoring System (CDAMS) has been implemented, which uses the same Work Breakdown Structure as the C/SCS, but substitutes pricing data for budgeted and actual costs. The system was revised in 1993. Elements for escalation and exchange rate control remain, but CDAMS now monitors progress payments based on C/SCS earned value claims.

Schedule. In accordance with the schedule shown in Figure 2, ships are planned to be delivered at about annual intervals from 1996 to 2004.

Australian and New Zealand Industry Program. The Australian and New Zealand Industry Program (ANZIP) for the ANZAC Ship Project has been developed in accordance with defense industry policy to maximise Australian and New Zealand Industry Involvement (ANZII). For supplies delivered under the ANZAC Ship Project, the prime contractor is committed to achieve a level of ANZ Content equal to 73% of the total contract price. A further 8% of the contract price is to be met through Defense Offsets. There is no contract specified work for the project.

Operational Requirements. McLean and Ball [6] discussed the strategic issues and the operational requirements for the ANZAC ships. In terms of documentation, the ANZAC Ship Project

developed from a brief capability statement. Whilst there is currently no endorsed Detailed Operational Requirement (DOR) for the project, the following technical documents collectively define the requirements:

- Combat System Tactical Operational Requirement,
- Ship Performance Specification, and
- Basis for Acceptance Into Naval Service.

Contract Design Baseline. West [4], the RAN's Chief of Naval Material in 1989, stated that:

> *"The ANZAC Ships are to be built to an existing design with minimum modification to meet the required characteristics, and with maximum Australian and New Zealand content within the bounds of practicality, cost and design integrity."*

The selected MEKO 200 ANZ design was based on the existing MEKO 200 PN design, under construction at that time for the Portuguese Navy. The contract for the first MEKO 200 PN had been awarded to a consortium of German shipbuilders on 20 November 1986. Construction of the lead ship, Vasco Da Gama, progressed with the keel being laid on 1 February 1989, launching on 26 June 1989 and commissioning on 18 January 1991.

During the Design Development Contract that preceded the competitive tendering phase, a number of major engineering changes were incorporated in the configuration of the MEKO 200 ANZ design to better suit the requirements of the RAN and RNZN. The changes affected the propulsion system, ship systems, communications systems, combat system and aviation systems integration. Other significant engineering changes were required to meet RAN requirements for the ship's thermal, acoustic, vibration and shock environment.

The Contract Design, the meaning of which is given by the RAN's Chief of Naval Staff [7], or "Allocated Baseline" was defined at contract award as a result of the Documentation Development Contract (DDC) and Best And Final Offer (BAFO) process, and covered the ship as a total system, including the systems and equipment proposed as an integral part of the tenderer's offer. The design baseline was defined by the contract specification, and supported by drawings, and engineering analyses prepared to demonstrate, at least by calculation, the performance of the ship and its principal systems. The design baseline, and the analysis involved in its development, provided the basis of the ship designer's warranty on performance.

Specifications for the Ship and its Combat System. The ANZAC Ship Specification forms a part of both the prime contract and the design sub-contract. The specification was developed to specify the characteristics and performance to be achieved by the vessel, and to define in detail all of the requirements necessary for the production design, construction and costing of the vessel to meet the characteristics and performance requirements.

In format, the specification is divided into groups, sub-groups and elements using the RAN's Technical Subject Code (TSC) system which is similar to the USN Ship Work Breakdown Structure (SWBS). The content of those technical groups dealing with Ship Systems was developed along the lines of the "General Specification for ships of the USN." For the groups, sub-groups and elements dealing with the Combat System, a specification format in accordance with MIL-STD-490A System/Segment Specification was developed, which follows the method of defining functional chains.

During the project development phase, the Commonwealth required the competing tenderer's to prepare Critical Item Product Function Specifications (CIPFS), providing a detailed description of the technical characteristics of a system/equipment considered to be critical to ship performance. In particular, they were to include statements as to the extent to which the system/equipment met generic RAN requirements.

The Ship Specification was originally intended to be "equipment non-specific". However, in the interests of standardization across the Class, a list of the major systems and equipment called the Standardized Equipment List (SEL) was introduced. The SEL formed the basis of the Shock Qualification List, which sought to confirm the performance of the nominated systems and equipment against the requirements for shock and vibration, and complemented the drawings, documents and engineering analyses delivered during the project development phase.

Modification to the Project Acquisition Strategy

At the time of contract award, it seemed to many of those involved that the MEKO 200 ANZ design baseline was clearly established, and that the ship as specified

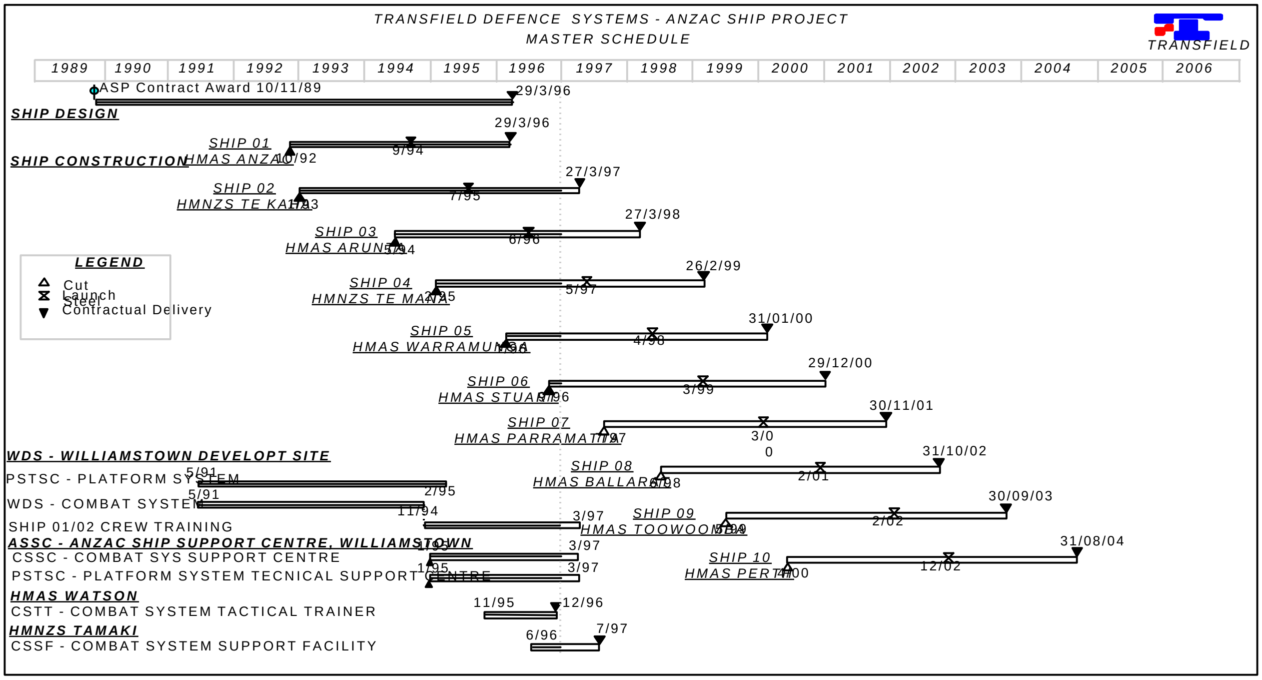

Figure 2. Project Master Schedule

could proceed on a clearly defined and low risk path to detail design and construction. The designer was confident that the warranted performance would be obtained, and the principal concerns were that the contract delivery schedule allowed little time to establish the high level of ANZ Industry Involvement (ANZII) that was required.

The procurement of major systems and equipment, especially long lead items, was a priority. For reasons of risk-management, the requirements of the prime contract were flowed down to potential suppliers. This included provisions relating to ANZII. In some cases, prospective suppliers considered themselves sufficiently well placed, either to not accept the ANZII requirements, or on becoming fully aware of the requirements, to increase prices accordingly. As a consequence of these actions, the prime contractor was faced with no alternative, in order to meet the contracted obligations for ANZII and also to control costs, but to competitively tender almost all of the equipments including those on the SEL. This strategy was supported by a clause negotiated into the ANZAC Ship Specification prior to contract award which stated:

> *"The Contractor shall have the right to propose alternatives to any of the Sub-contractors and equipments in the Standardized Equipment List (SEL). Changes shall be proposed pursuant to Clause 49 of the Contract. The Project Authority's approval for such proposed changes shall not be unreasonably withheld."*

It was recognized that while this strategy would assist in meeting the objectives of high ANZII and cost control, it would have a negative impact on both schedule and the "low risk" aims of the project. However, after analysis of all of these factors, the client was prepared to accept that the advantages of this strategy far outweighed the impacts and agreed that the prime contractor proceed on this basis. Despite an overall impact on the engineering design schedule of about 13 months in contractual terms, which averaged around 11 months in practice, the client was prepared to accept a delay of 5 months to the delivery of Ship 01 and a delay of 1 month for Ship 02.

In dealing with configuration changes proposed by the prime contractor, the Commonwealth adopted a flexible approach which is discussed by Malpas [8]. This shifted the emphasis from the original strategy of building "an existing design with a minimum of changes", to the maintenance of "function and performance." Under these circumstances, the ANZAC Ship Specification, based as it was on the existing MEKO 200 PN design, proved to contain a level of detail which was inappropriate to either the prime contractor, or the Commonwealth.

Consequences of the modified strategy were delays in the availability of Contractor Furnished Information (CFI) for systems and equipment pending source selection, resulting in delays in ship design development, and the need to prepare sub-contract amendment proposals to advise the technical and commercial implications of the configuration changes.

The many changes in configuration clearly had the potential to impact on the performance warranted by the designer. There were periods between contract award and delivery of Ship 01 when the risk of not meeting the requirements was carried by the prime contractor and the system supplier. In the event, the design integration was satisfactory and the designer's warranty on ship performance maintained.

MEKO Naval Ship Design Philosophy

The MEKO design philosophy has been widely documented

elsewhere, and it is not the purpose of this paper to review the detailed characteristics of the MEKO 200 ANZ. The principal features of MEKO vessels have been described by Sadler [9], and Ehrenberg and Schmidt [10].

According to Dunbar [11], the acronym MEKO translates as "Multi-Purpose Combination", and the design concept includes:

- *"modularity, with the use of a variety of standard size modules and pallets for the installation of weapon and electronic systems;*
- *standardization, with the development of standard structural, electrical/electronic and ship system interfaces for the integration of standard sized weapons and electronics modules; and*
- *survivability, with the individual ship section independence of ventilation, seawater, firefighting, electrical power distribution and data transfer systems."*

The design philosophy is one in which a naval ship is regarded as an "integrated system." This total system is broken down into functional systems and sub-systems in accordance with a four digit coded hierarchy known as the Index of Materials and Services (IMS).

In accordance with the MEKO philosophy, there is also a pre-defined breakdown of the ship into modules for the hull structure, superstructure, and outfit. The hull structure is divided into six modules M1 to M6, and the superstructure is also divided into six modules A1 to A6. Each of the hull structure modules is further sub-divided into structural units and sub-units, as shown in Figure 3.

The outfit modules/functional units include:

- 2D Radar container,
- 127 mm Gun Container,
- Communication Control 1 Container,
- Communication Control 2 Container,
- Communication Control 3 Container,
- Command and Control Equipment Container,
- Communications Transmitter,
- Sonar,
- Target Indicating Radar,
- Ventilation Modules - 9 off,
- Operations Room Pallet, and
- RAST Equipment Pallet.

For the Mk 41 VLS launcher, whilst not designed as a MEKO functional unit, the system-ship integration facilitates installation as for other MEKO functional units.

Design features of the MEKO 200 ANZ. Pine [12] described the specific features of the MEKO 200 ANZ and concluded that:

> *"the ANZAC Ship design offers four innovations to the designers of the 21st Century Surface Combatant:*
>
> - *Firstly, the modular/functional unit design concept which allows flexibility in equipment selection throughout the life of the ship. It also provides improved survivability with its fully independent ship sections and allows a distribution of resources during the ship build phase.*
> - *Secondly, the automated Control and Monitoring System offers many advantages in supporting the Propulsion, Electrical, Damage Control and Auxiliary systems.*
> - *Thirdly, the system redundancy installed throughout the ship.*
> - *Finally, the independency offered by the Combat System software."*

The Control and Monitoring (C+M) System is described by Cruickshank [13]. The basis for the design was the MEKO 200 PN. The graphic pictures were modified to reflect the configuration of the systems on board the MEKO 200 ANZ, and the measuring points list was also modified. Functional descriptions were prepared for the Propulsion System, the Electric Plant, and the Damage Control and Auxiliaries. These three documents described how the various ship systems were intended to be operated via the C+M System in sufficient detail for the system supplier to proceed with the design of the system software. At this stage, the supplier changed the technological basis of the system, from the NAUTOS 2 system used on the MEKO 200 PN, to the NAUTOS 4 system which used the S5 industrial based plc system used on the MEKO 200 HN. Following criticism of the graphics system, the graphics technology was also subsequently changed to a "Windows-based" system.

The approach adopted for managing environmental engineering issues involving acoustics, vibration, and shock is discussed by Smallwood [14]. As a general rule, system suppliers are responsible for the selection and supply of suitable shock/vibration mounts.

The management of Electro-Magnetic Interference/Compatibility (EMI/EMC) issues proved complex, due to the procurement of systems and equipment to several different standards, which could not be directly related.

Design Changes. Malpas [8] documented the characteristics of the MEKO 200 ANZ design, and described some of the configuration changes incorporated during the design process, which included:

- Propellers,
- Ships Boats,
- Hangar Gantry Crane,
- Paint Scheme,
- 5" Gun,
- Flight Deck Firefighting,
- Control and Monitoring System, and
- Administrative Local Area Network.

Other significant configuration changes, in terms of engineering integration, included:

Platform:

- Cross-Connection and Diesel Gearboxes,
- Fluid Couplings,
- Propulsion Shafting,

- Fin Stabilisers,
- Fuel and Lube Oil Purifiers,
- Combustion Air System and Uptakes for the Propulsion and Generator Diesels,
- Gas Turbine Engine Control Module,
- Steering Gear,
- Fire Pumps,
- Salvage Pumps,
- Hangar Door,
- Anchor Windlass,
- Anchor and Mooring Capstans,
- Vacuum Sewage Treatment Units,
- Batteries,
- Commissary and Laundry Equipment,
- Ballistic Protection,
- Cathodic Protection, and
- Security Containers.

Navigation and Communications:

- Ship's Navigation Data System,
- GPS Receiver, and
- Communications Electronic Surveillance Measures.

Combat System:

- Combat System Local Area Network,
- Target Indicating Radar,
- Electronic Surveillance Measures,
- Identification Friend or Foe System,
- Closed-Circuit Television System,
- Helicopter Visual Landing Aids, and
- Towed Array Sonar System.

The scope of the above design changes, when considered together with the configuration changes incorporated prior to contract award, represented a substantial engineering impact on the existing MEKO 200 PN design.

Production of MEKO Frigates in Germany

Experience in the design and construction of first-of-class vessels has shown that build time and cost are related, and efforts are aimed to minimise the elapsed time from contract award to delivery, which includes the lead time for engineering, design, and procurement. The MEKO design philosophy of modular construction, facilitates the parallel design and production of weapons, sensor, electronics and outfit modules (functional units and pallets), and assists in the reduction of the build time.

Figure 4 (from [15]) shows a typical comparison of the time frame between contract award and commissioning for a conventional frigate, versus a MEKO frigate. For the design and construction of the MEKO 200PN, an elapsed time of approximately 50 months from contract award to delivery was achieved. By comparison, for the design and construction of an F123 destroyer, an elapsed time of 62 months from contract award to delivery was

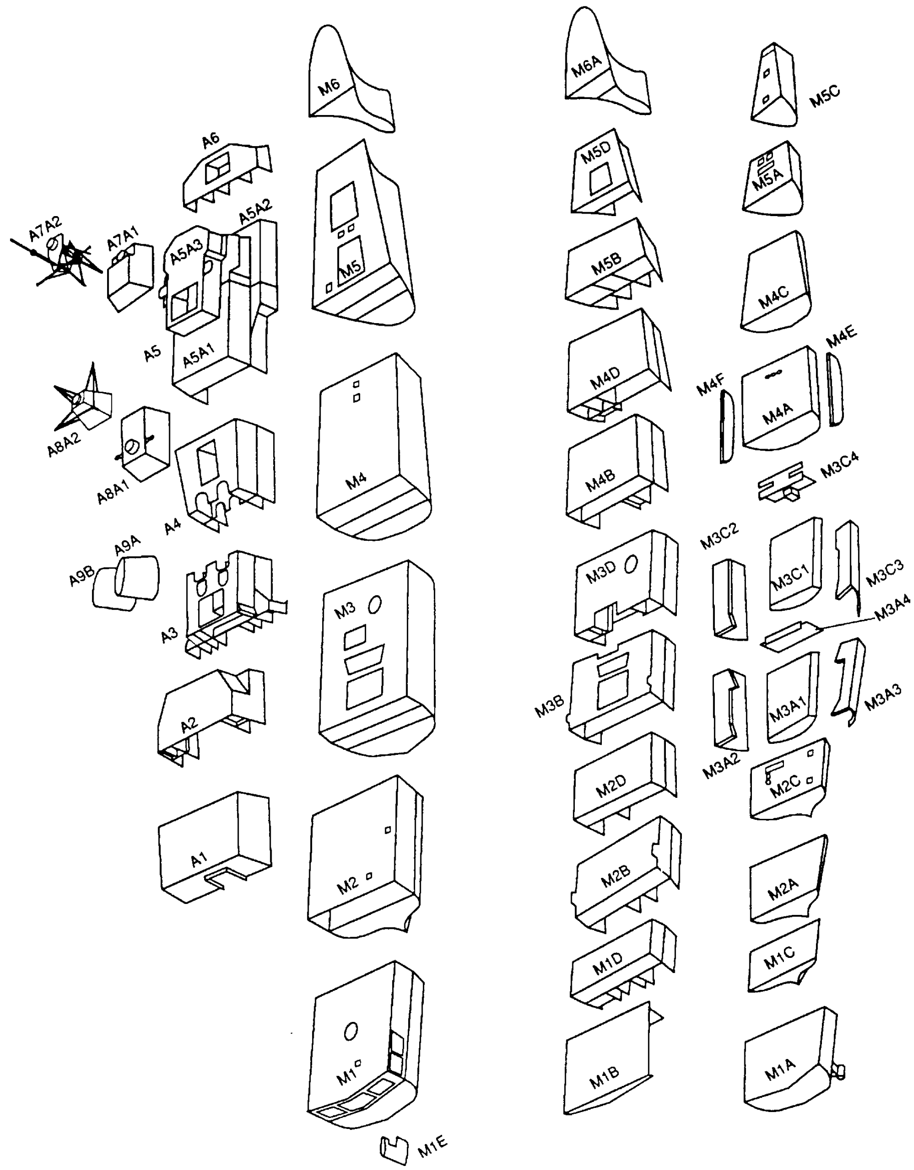

Figure 3. Modular Construction of the MEKO 200 ANZ

achieved.

The build strategy developed for the production of steelwork is consistent with the Hull Block Construction Method [16]. The fairness of structural modules gives an indication of good dimensional control during fabrication, and line heating is used as a technique to remove distortion.

The ship design process ensures a high level of outfit planning and integration with steelwork production, and is further enhanced by the advantages offered by the MEKO system of outfit modules. In the construction of first-of-class vessels, the achievement of high levels of outfitting prior to the erection of hull and superstructure modules on the berth is an objective, but one which is dependent upon the timely availability of design information, and any additional costs incurred for earlier delivery of equipment.

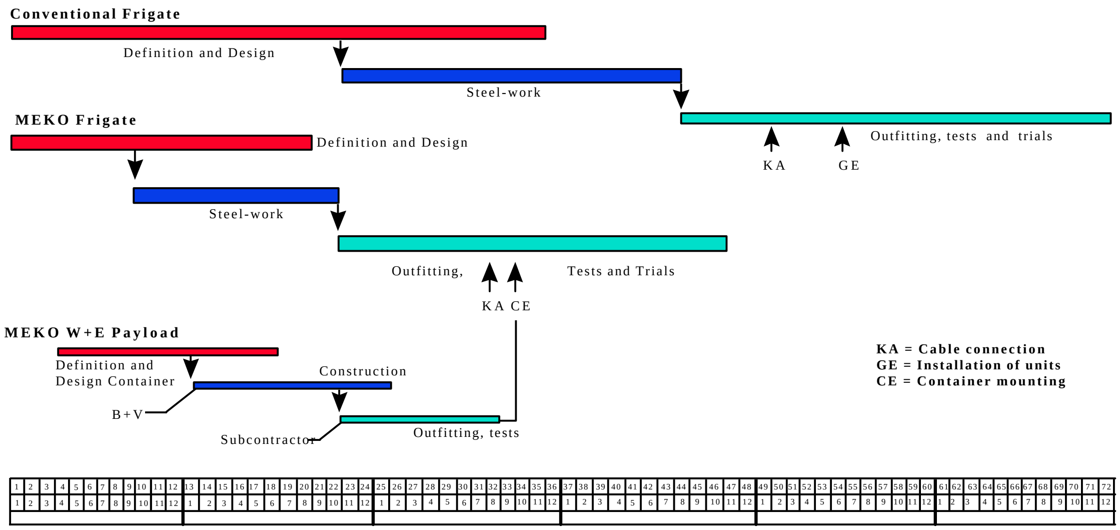

Figure 4. Time Frame Between a Contract Coming in to Force and Commissioning

Change Process - Comparisons	
Williamstown Dockyard	Transfield Defence Systems
23 Unions	3 Unions
30 Awards	1 Award
390 Classifications	2 Classifications
Demarcation Endemic	Demarcation Free
180 Allowances	Nil Allowances
Various Types of Leave	Standard Leave
Recruitment Geared to Programme Peaks	Recruitment Geared to Programme Troughs
Idle Time	No Idle Time
Industrial Lost Time 10%	Industrial Lost Time 0.1%
Productivity Extremely Low	Productivity Increased by 600-700%
2,400 Employees	1,200 Employees
Paid According To Classification	Paid According to level of Skill
Award is multi-skilled, demarcation free and fully flexible. Based on the concept of employees completing whole tasks as long as it is safe, legal, sensible and the employee is competent. That is the simple basis of multi-skilling.	

Table I

Production of ANZAC Ships in Australia

Transformation in Naval Shipbuilding Culture at Williamstown. The transformation effected at Williamstown from being a government-owned Naval
Dockyard to a privately-owned industrial enterprise
specialising in defense systems, has required a significant change in the culture of the organisation. Table I (from Horder [17]) provides a summary comparison of the changes that were accomplished during the transformation.

The successful resolution of the major issues associated with the above changes occurred during the tendering process for the ANZAC ships, prior to the award of the prime contract. At that time, the new owners of the shipyard were engaged in the construction of FFG-7 Class ships under the Australian Frigate Project.

Procurement. The objective to maximize the level of Australian and New Zealand Industry Involvement (ANZII) was a significant driver behind the strategy adopted for the procurement of systems, equipment and material. Using competition to gain commercial leverage, Requests For Tender (RFTs) were issued progressively in priority order based on an assessment of the procurement lead time and the criticality of engineering information to support the design process.

To support the procurement strategy, purchase specifications

defining the technical requirements and the scope of supply/work, were prepared in terms that were sufficiently generic to allow a number of suppliers to bid. The purchase specifications also needed to contain sufficient information to allow prospective Australian and New Zealand suppliers to compete, some of whom were unfamiliar with the requirements typical of naval shipbuilding projects, including performance, shipboard integration, and environmental qualification for acoustic, vibration, shock and EMI/EMC performance.

Some prospective suppliers were also unfamiliar with the type and volume of documentation and information required to support naval shipbuilding projects, including product/system specifications, interface specifications (system-system and system-ship), drawings and detailed engineering data.

In many instances, the required performance of the ship as a total system, and the physical constraints of shipboard integration, such as available space and weight and physical interfaces to other systems and the ship, were needed as input parameters to the purchase specification. This led to a complex and iterative dialogue between the supplier, the prime contractor, and the designer, who was at "arms length" from the supplier.

The contracting structure that resulted from this procurement process, was quite different to that developed for the construction of the existing MEKO 200 PN design.

From the original project strategy, it was envisaged that the required level of ANZII would be achieved mainly by the manufacture and/or assembly in Australia or New Zealand of the systems and equipment within the MEKO 200 ANZ design baseline, as nominated in the SEL, in order to maintain configuration "form, fit, and function." Most of these items were of European origin. In the event, ANZII was achieved by the substitution of alternative systems and equipment. ANZII obligations upon sub-contractors resulted in arrangements between overseas suppliers and local manufacturers, such that a substantial package of work was performed in Australia and New Zealand.

An organization known as the Industrial Supplies Office (ISO), with offices in each Australian State and Territory, aimed at facilitating the replacement of imported products with locally manufactured items, played an important role in supporting the procurement process.

Early in the procurement process, the allocation of responsibility for the preparation of purchase specifications was an issue between the prime contractor and the ship designer, aggravated by contradictions within the design sub-contract. These contradictions can perhaps be explained by the modification in project strategy outlined earlier, and the procurement strategy whereby generic purchase specifications needed to be developed by the purchaser, rather than detailed specifications being developed by the selected supplier.

System Integration. Following the award of procurement sub-contracts, system integration was able to progress. In terms of engineering documentation, this activity involved the preparation by the supplier of product or system specifications, and interface specifications for system-system and system-ship integration.

The preparation of system and interface specifications is an iterative process between the supplier(s), prime contractor, the combat systems integration sub-contractor, and the ship design sub-contractor. The finalization of the documents, involving the incorporation of comments, and the implementation of configuration changes to ensure proper system integration, was in some cases protracted. These documents formed attachments to the original procurement sub-contract.

As a consequence of the modification in the project acquisition strategy referred to earlier, its impact upon risk management generally, and the need to maintain the design sub-contractor's general warranty on performance, a difficult situation developed over time because neither the original procurement sub-contracts nor the system and interface specifications had been finalized and formally "signed-off" by the design sub-contractor to accept responsibility for overall compliance with the ANZAC Ship Specification. Consequently, there was some doubt as to the basis upon which the design sub-contractor's warranty on performance could be supported. This issue also had implications subsequently for the preparation of test procedures required for the Production Test and Evaluation Program, which needed to be based on the purchase specifications.

To support the system integration activity, the prime contractor took responsibility for the design and construction of the Williamstown Development Site (WDS) as a land-based test site for the engineering development and integration of the Control and Monitoring System and the Combat System. The design and construction of the WDS was on the project's critical path, and was separate from the design sub-contract. To the extent that the design of the WDS was dependent upon the design of the ship, this became an area of some difficulty, since the schedules for the availability of design drawings were not related.

Specialist support was obtained for the following system integration roles:

- Command and Control System Integrator,
- Combat System Simulation,
- Communications Systems Integrator,
- Navigation Systems Integrator, and
- Control and Monitoring System Integrator.

Ship Production (Build Strategy)

The build strategy developed for the construction of the ANZAC frigates centred around the geographic distribution of work. For the first and second ships, all modules were fabricated and erected in Williamstown. For the third and possibly subsequent ships, hull modules M4 and M5 are being fabricated in Newcastle, and all superstructure modules A1 to A6 are being fabricated at Whangarei in New Zealand. Modules constructed off-site are shipped to Williamstown by barge.

The shipyard underwent an extensive modernization program during the late 1970's and early 1980's, in preparation for the construction of FFG-7 frigates. The modernization included the construction of a new dual berth slipway, new cranage, installation of an automated plate preservation line, numerically-controlled cutting equipment, a module blast and painting facility, an extension to the pipe fabrication shop, new outfit workshops, an outfitting pier, material storage warehouse, and administration offices.

For the construction of ANZAC frigates, a new module hall has been built, and two multi-wheeled transporters have been purchased, each capable of moving modules weighing over 200 tonnes from the module hall to the slipway. Attention has also been given to improved access to ships on the slipway, and to providing a healthy shipboard environment that is clean and safe.

The ship production process for the ANZAC frigates, superimposed upon the physical layout of the shipyard, is illustrated in

Figure 5. The Hull Block Construction Method is evident in the construction of modules. Outfit planning is increasing the level of outfit components installed in modules “On Block”. The revised paint specification introduced as a design change on Ship 01 was originally developed for the construction of FFG-7 frigates under the Australian Frigate Project, and incorporates the basic philosophy of the Zone Painting Method. Consequently, progress has been achieved on several fronts towards the goal of Integrated Hull Construction, Outfitting and Painting [16].

Limiting the impact on the delivery schedule for Ship 01 to five months, given the additional lead time averaging about eleven months required for procurement, and design development on the part of suppliers and the design sub-contractor, required a range of measures to be taken. This included the use of “preliminary” information in a number of areas, particularly for hull construction and the electrical system installation.

Test and Evaluation Program. The structure of the Test and Evaluation Program is divided into:

- Development Test and Evaluation (DT&E),
- Production Test and Evaluation (PT&E), and
- Operational Test and Evaluation, (OT&E).

DT&E is a prime contractor responsibility, but the scope of this test activity for the ANZAC Ship Project is limited. OT&E is a Commonwealth responsibility conducted by the customer navy subsequent to ship delivery and prior to acceptance into naval service. The major testing activity in support of ship construction is PT&E.

Production Test and Evaluation (PT&E) includes the following Categories:

- Category 0 - Design & Eng. Development Tests,
- Category 1 - Factory Tests,
- Category 2 - Environmental Tests,
- Category 3 - System Development Tests,
- Category 4 - Shipyard Tests, and
- Category 5 - Sea Tests.

Pre-Construction Testing: Pre-construction testing comprises Categories 0-3 testing.

Construction Testing: comprises all Category 4 and 5 testing. All construction testing (except Stage 1 of Category 4 tests), is incorporated into an Integrated Test Package (ITP) after first ship validation of all Category 4 and 5 tests has been completed. The ITP consists of the test matrix, test sequence network, test procedures, and test index.

Test Stages Construction Testing (i.e. Category 4 and 5 testing) is further divided into seven stages:

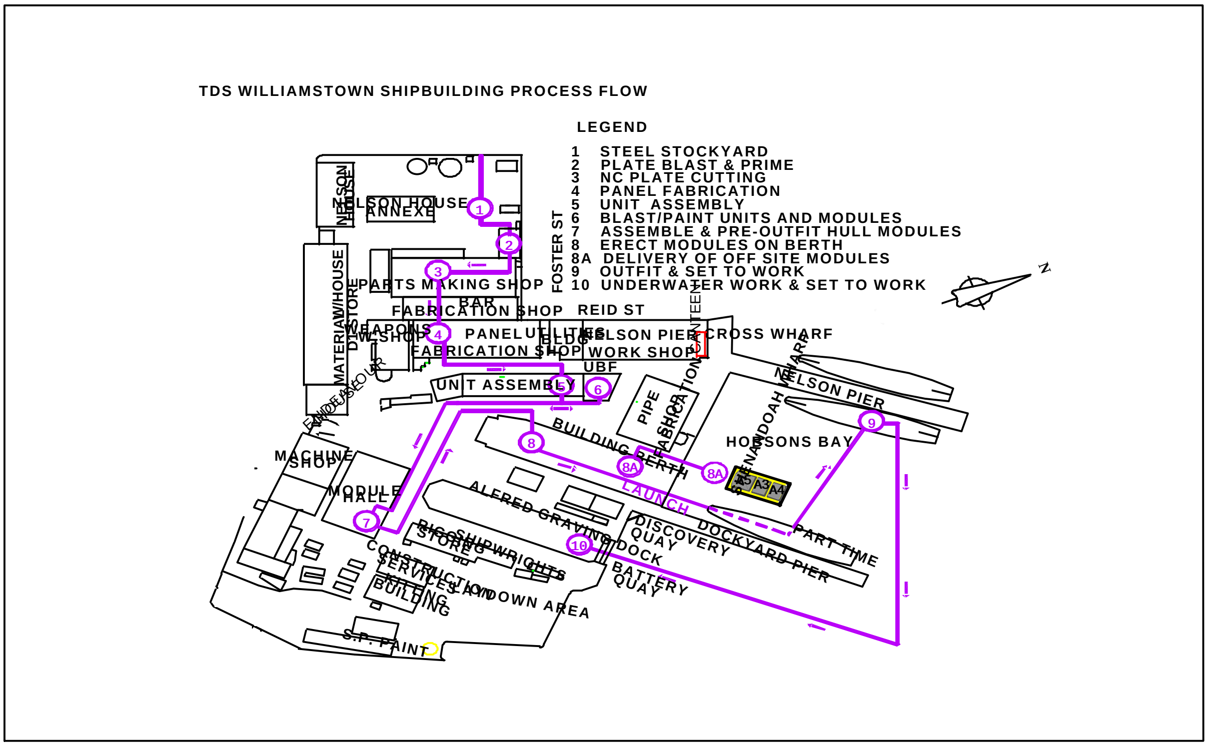

Figure 5. Ship Production Process for the ANZAC frigates.

- Stage 1 - Quality Control Inspections/Tests,
- Stage 2 - Installation Inspection and Tests,
- Stage 3 - Equipment/Module Level Tests,
- Stage 4 - Intrasystem Level Tests,

- Stage 5 - Intersystem Level Tests,
- Stage 6 - Special Tests, and
- Stage 7 - Sea Trials.

By the end of 1995, with the extent of changes incorporated in Ship 01, the original low risk strategy of an ‘existing design’ could scarcely be considered valid. Much rested on the outcome of Contractor’s Sea Trials (CSTs) to provide proof of performance.

The Category 5 Contractors’s Sea Trials activity was conducted during January and February 1996, and successfully demonstrated that the performance of Ship 01 exceeded both the requirements and the expectations of the RAN.

ANZ Industry Program.

In order to meet the commitment to ANZII under the prime contract, involving 73% ANZ Content and an 8% Defense Offsets obligation, overseas suppliers were encouraged to establish facilities in Australia or New Zealand, or to establish partnerships with local companies, to manufacture products required for the project.

As shown in Figure 6, the commitments to ANZII are on target. More than half of the obligation under the prime contract for ANZ Content has been spent within Australian and New Zealand industry, and a competent and capable local supplier base has been established. Business Victoria, a Department of the State Government of Victoria, reported that:

> *“The project has expanded local industry capabilities across a broad range of disciplines. It has brought together a network of over 1,300 suppliers throughout Australia and New Zealand. Many of the companies are producing products they have not produced before - from advanced software programs for ship systems, to valves, ventilation ducting, pumps, refrigeration units, furniture, recovery boats, engines, electric driers, switchgear and specialist castings.”*

Integrated Logistic Support.

The prime contract for the ANZAC frigates includes a comprehensive requirement for Integrated Logistic Support (ILS) necessary to ensure that the ships are effectively operated, maintained and supported throughout the life of the ANZAC Class. The elements of the ILS package include maintenance planning, supply support, documentation, manpower, training, technical documentation, facilities, storage and transportation, support and test equipment, and computing support.

An innovation for the ANZAC frigates is the introduction of an ILS performance warranty. The prime contractor has guaranteed an Operational Availability of 80% for a period of 10 ship years. This covers an elapsed period of 4 years from delivery for Ship 01, 3 years for Ship 02, 2 years for Ship 03, and 1 year for Ship 04.

The ANZAC Ship Support Centre (ASSC) has been established at Williamstown to support the development and integration testing of both the platform Control and Monitoring System and the Combat System, and to train navy personnel. The ASSC will be used to provide ongoing training, and to support system maintenance and development to incorporate technological changes. It offers the RAN the important capability to provide parent navy support, and to contribute to the Australian Government’s aim for a self-reliant defense capability, rather than depending on an overseas navy, as has been the case in the past.

PRIME CONTRACT REQUIRES 73% ANZ CONTENT + 8% OFFSETS.

AS OF DECEMBER 1996 THE PRIME CONTRACTOR HAS COMMITTED $A 2,413M AGAINST A PLANNED $A 2,372M OF ANZIP IN SUB-CONTRACTS.

THE TREATY GUARANTEES NZ $ 585M OF NEW ZEALAND INDUSTRY INVOLVEMENT.

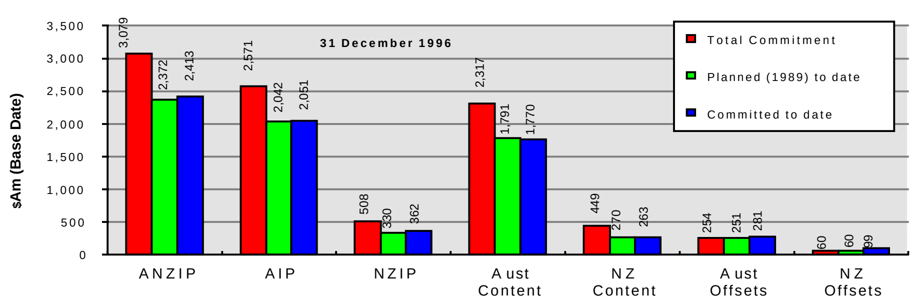

Figure 6. Australian and New Zealand Industry Involvement

PROGRESS TOWARDS INTERNATIONAL COMPETITIVENESS

International competitiveness in naval shipbuilding is considered to be dependent upon several factors; the principal ones being the technology incorporated in the product, the cost of the product, and the delivery time. In the context of the ANZAC Ship Project, Horder [17] claimed it necessary to achieve productivity levels comparable with Germany by Ship 03, which is planned to be delivered in 1998. In 1995, White [18] claimed that international competitiveness had been achieved in productivity, quality and cost, but gave no quantitative evidence to substantiate the claim.

A report entitled "Best Practice in Action" [19] was prepared under the Australian Best Practice Demonstration Program, sponsored by the Australian Manufacturing Council and the Department of Industrial Relations. It presents a collection of the executive summaries of case studies developed on 42 projects. Details of the case studies, including one which relates to the prime contractor for the ANZAC Ship Project, have been published in a book entitled "The Best Practice Experience" [20]. A book by Rimmer et al [21] entitled "Reinventing Competitiveness - Achieving best practice in Australia" also draws on the case study material and other literature. "Best Practice in Action" [19] describes best practice as: *"a comprehensive and integrated cooperative approach to the continuous improvement of all facets of an organisation's operations. The projects are grouped under the particular characteristics in which they excelled, which included:*

- ***Leadership/Vision** - shared vision and strategic plan, commitment and leadership of the Chief Executive Officer;*
- ***Industrial Relations Reform** - co-operative industrial relations;*
- ***Focus on People Issues** - commitment to continuous improvement and learning, innovative human resource management, integration of environmental management practices;*
- ***Work Organisation** - flatter organisational structures, pursuit of innovation in technology, processes and products;*
- ***External Links** - focus on customers, closer relations with suppliers, development of networks; and*
- ***Benchmarking** - development of performance measurement systems and benchmarking."*

In September 1994, the Australian Science, Technology and Engineering Council (ASTEC) commenced a study called "Matching Science and Technology to Future Needs: 2010" to investigate what Australia's future science and technology needs are likely to be by the year 2010. The study has two major components: the "Overview" and the "Partnerships". The Overview component involves the identification of ASTEC's key issues in 2010 looking at Australia's social, economic and environmental needs. The Partnership component of the study involves a more in-depth analysis of the key issues facing Australia in a number of areas. Five Partnerships have been established, one of which is the ASTEC Shipping Partnership. In its report [22], the Shipping Partnership recommended that a suitable set of benchmarking measures be identified, so that a basis for comparisons of international competitiveness and continual improvement can be established for the Australian shipbuilding industry.

Attempts at comparisons of international competitiveness in naval shipbuilding programs are undoubtedly difficult because of the specialised nature of the work, and government policies which may give preference to work being performed in-country, and not necessarily in the most effective or efficient manner. These and other economic and political factors lead some to conclude that comparisons of international competitiveness are not feasible, practical or worthwhile. However, if such an attempt were to be made, the comparison would need to be between similar activities. For first-of-class ship production, the comparison would need to include the engineering, design, and procurement activities as well as production, test and trials activities over the total time from contract award to delivery. A comparison of first-of-class production man-hours with follow ship production man-hours is considered inappropriate.

A methodology which has been applied to assess the competitiveness of U.S. naval shipbuilders against foreign commercial shipbuilders, was reported by Storch, Clark and Lamb [23]. The paper summarises a study conducted by Storch, A&P Appledore and Lamb [24] for the NSRP, and uses Cost (in US$) per Compensated Gross Ton (CGT) as a measure of international competitiveness for both commercial and naval vessels.

Efforts to undertake a direct comparison of performance between shipyards in Australia and overseas

have not as yet been practicable. However, there is a general view that Australia is approaching a level of international competitiveness in naval ship construction and that the costs of construction in Australia are no higher than the costs in either Europe or the U.S. Further work is needed to make an accurate assessment of the costs of naval shipbuilding in Australia versus overseas.

FURTHER DEVELOPMENT AND OUTLOOK

In the course of the ANZAC Ship Project, problems have occurred along the way, but these have been resolved. The success of the project to date bodes well for the future of naval shipbuilding in Australia, subject to there being a sufficient and sustainable demand from the domestic and/or regional markets.

Australian defense procurement is based on a policy of seeking open and effective competition as a means to demonstrate that best "value for money" has been obtained for the Australian tax payer. However, the need to ensure competition has helped to create a shipbuilding capacity which exceeds the long term steady-state demand of the Australian Department of Defence. Consequently, further industry re-structuring and rationalisation may be inevitable to reduce capacity.

For future RAN ship acquisition projects, there is a need for long term strategies that provide an opportunity for industry to provide some input to the strategy development.

Following the review by Gabb and Henderson [25, 26] of Australian Department of Defence specification practices, it is likely that future defense procurement will be conducted against a "requirements specification" pitched at the relatively high level of "function and performance," rather than against a detailed "technical specification" which documents the function, performance and technical characteristics of the "solution" or "product" offered.

The Quality Standard ISO 9001 (1994) also includes clauses relating to design verification and validation which effectively require objective evidence to demonstrate traceability from the "requirements" through to the "design solution." For compliance with the standard, increased rigour is needed in both the formulation of requirements, and their implementation through the design, construction and testing process.

The procurement of critical/major systems and equipment involves a substantial technical activity, and good communication is necessary between the customer, the prime contractor and the ship designer. An arrangement whereby the major parties involved have visibility of the technical and commercial aspects of the procurement process could help to ensure adequate lead time for the development of specifications and engineering data, and would do much to overcome the difficulties encountered on the ANZAC Ship Project. To support project development, competitive pre-qualification, short listing, or possible source selection of critical/major systems and equipment could be considered as part of the acquisition strategy. This could be performed by the Commonwealth, or by a joint arrangement also involving the prime contractor and the ship designer.

Proposals for the indigenous design of a future surface combatant to replace Australia's core force of DDG's and FFG's [27] must overcome a bureaucratic aversion to the cost and perceived risk of large scale engineering development and design projects. This is likely to continue to make the competitive selection of an overseas-sourced design an attractive option. Assuming that the defense policy for ANZII continues, consideration regarding its implementation is an important part of the project acquisition strategy.

In the acquisition of future surface combatants, both Defence and Industry should seek to learn from the ANZAC Ship Project. Key issues to be considered are:

- The Australian Government policy of seeking self-reliance in defense places priority on developing and sustaining a naval shipbuilding industry capability, not solely on the acquisition of ships for the Navy.

- The objective of the ANZAC Ship Project acquisition strategy to minimize changes to an overseas-sourced existing design proved to be incompatible with the objective of maximising the level of ANZII within a fixed-price contract.

- An acquisition strategy should recognize "change" as a reality, and plan accordingly. It is expected that such recognition will result in a better definition of the scope of changes required, if an overseas-sourced design is considered for construction in Australia, with an associated streamlining of procedures.

- The need exists for a more robust systems engineering management framework for RAN ship acquisition projects, covering requirements analysis and definition, specification practices and engineering standards, procurement, engineering development, design, production, and test and

evaluation.

- Capability upgrades should be pre-planned and scheduled as an integral part of the change management process, both to serve the purpose of maintaining pace between the product and the level of technological change, and also as a means of sustaining the key engineering skills and capabilities developed through the ship acquisition process.

- "In-service support should be addressed as an integral element of the acquisition process, and also as a means of sustaining the key engineering skills and capabilities developed through the ship acquisition process.

A new policy of Evolutionary Acquisition (EA) is under development by the Australian Department of Defence, intended primarily for application to high technology projects which involve large scale software development and system integration. Henderson and Gabb [28] describe the concepts of EA which have resulted from work done in the US at the Defence Systems Management College, and state that a major reason for the introduction of EA for the procurement of complex systems is because users have great difficulty in specifying many of their detailed needs. Traditional acquisition strategies often fail to take this into account and the stated user requirements remain static after the development contract is signed. Additionally, advances in technology are not easily incorporated into systems when the advances occur during development.

The main thrust of EA is the specification, design, implementation, testing, delivery, operation and maintenance of systems incrementally. Delivery of each incremental release increases the capability of the system until complete. Users have early access to system releases and are encouraged to provide feedback on performance. This is used to shape the system as it evolves into its final form. If this approach is followed in a disciplined manner, a more responsive system should result.

It would seem that Evolutionary Acquisition is seeking to deal with some of the factors which, for the ANZAC frigates, emerged as difficulties during the procurement, design and production phase. The concept, whilst primarily intended for software intensive projects, such as Command, Control, Communications and Intelligence (C^3I) systems, might also have application to complex naval ship design and construction projects. In this respect, the provision of margins, either as "Space and Weight" or "Fit For But Not With," within the contract design baseline of the ANZAC ships is indicative of planning for future capability enhancement.

Overall, there are many factors to be taken into account and balanced, and the development of an appropriate acquisition strategy represents both an opportunity and a challenge to those involved in planning the design and production of Australia's next generation of surface combatants.

PROJECT ACHIEVEMENTS

The ANZAC Ship Project has been successful in delivering the first-of-class, HMAS ANZAC, to the RAN. The ship has successfully completed its PT&E program, and the Combat System is fully functional. Formal acceptance into naval service of HMAS ANZAC by the RAN is expected in mid to late 1997, following a period of OT&E. The second ship, HMNZS Te Kaha, is expected to be delivered to the RNZN in March 1997. The Combat System Tactical Trainer at HMAS Watson in Australia has been delivered. The Combat System Tactical Trainer for New Zealand and the ANZAC Ship Support Centre at Williamstown in Australia will be delivered in early 1997. Delivery of these major items is within the budget and the agreed schedules.

The engineering achievements of the ANZAC Ships are described by Welch [29], the RNZN Chief of Naval Staff, in a paper to the 1997 Annual Conference of the Institution of Professional Engineers New Zealand. Factors which have featured in the successful outcome include the development of an increasingly self-reliant industry capability, the transfer of technology, the development of Australian and New Zealand industry involvement, improvement in the performance and competitiveness of the Australian naval shipbuilding industry, and the potential for export market opportunities.

The industrial infrastructure developed to support the ANZAC ship construction activity is also capable of providing through-life support. This capability will be tested when the RAN invites industry to bid to provide ANZAC Class In-Service Support.

The ANZAC Ship Support Centre, together with appropriate commercial support, provide the means by which the RAN can provide the full range of services required of a parent navy. The ASSC and the Combat System Tactical Trainers at HMAS Watson in Sydney and at HMNZS Tamaki in New Zealand, will provide comprehensive navy crew training facilities.

Achievements on the ANZAC Ship Project have been recognized within Australian industry with the announcements in 1996 of two awards, namely: the

Institution of Engineers, Australia "Engineering Excellence Award", and the "Australian Defence Quality and Achievement Award" for Projects over A$ 20 million.

The task remains to deliver another 9 ships, with the possibility of a major capability upgrade during construction for Ships 07 to 10.

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reductions in cost and cycle time being realized. During the development of this application, the team recognized that significant non-recurring engineering and planning were required to support implementation.

In 1995, based upon this machinery unitization experience and knowledge of foreign shipbuilding developments during the 1970's and 1980's, NASSCO management developed the concept of a Standard Machinery Unit. This approach was based upon the standardization of system architecture and engine room arrangements, as well as the use of standard unit structural and system interfaces that would be applicable across a wide range of ship types and main engine horsepower.

The development of this concept and its application to a specific ship design will be described herein.

DEVELOPMENT APPROACH

In early 1996, NASSCO was awarded a subcontract to further develop the Standard Machinery Unit concept as part of the ERAM portion of the Navy's Mid-Term Sealift Technology Development Program. To support this development, a standard machinery unit project team was assembled including personnel from engineering, manufacturing engineering, planning, production, materials, and cost engineering. The project team was supported by both internal and ERAM Project Steering Committees.

The technical development of the project focused on commercial ship machinery spaces using slow speed diesel power plants ranging from 10,000 to 50,000 BHP. Parametric analysis was used to systematically evaluate the key product variables and to select a single or family of similar solutions as appropriate. The key parameters or product variables considered included:

- Ship type
- Ship size and speed
- Engine room location
- Main engine vendor
- Main engine horsepower
- Owner options

A critical part of the development process included benchmarking of state-of-the-art marine and U.S. land-based industrial plant design and construction practices as described below.

BENCHMARKING

The team benchmarked "World Class" land-based and shipbuilding practices in order to evaluate the potential for applying advanced unitization concepts to shipbuilding. The unitization approaches observed in each case were customized to the fabricator's or builder's individual requirements. A prevalent strategy in land-based applications was to complete the majority of fabrication in the central production facility thus minimizing the need for a large work force and support facility onsite in a remote or rugged location. In shipbuilding applications, the primary driving force for unitization was concurrent construction of the ship's hull and the machinery systems.

Shipbuilding Applications

The first step of the shipbuilding benchmarking effort was to identify ship construction facilities presently applying advanced unitization concepts. Conventional shipbuilding practices were also reviewed to best evaluate the advantages and disadvantages of unitization.

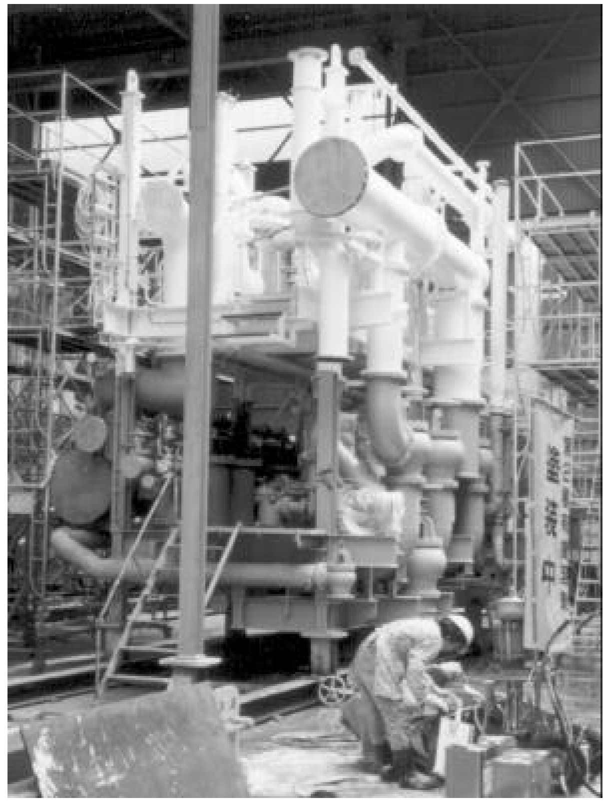

Fig. 1 Grand Unit at IHI's Aioi Facility

Ishikawajima-Harima Heavy Industries (I.H.I.), of Japan, has been building merchant ships since 1990 using a unitization concept employing standard machinery units. These units are fabricated at the Aioi Works, joined into a grand unit, as shown in Fig. 1, and then barged to their Kure facility for shipboard erection. The grand unit is installed along the forward engine room bulkhead immediately forward of the main engine.

IHI uses parametric design in that a large percentage of the modules are reused from ship to ship with some minor modification. Both their system design and detail design start with a "base standard" which is then modified as needed.

Another shipbuilder who makes use of large standard machinery units is Thyssen Nordssewerke, of Germany. To date they have applied their version of unitization to slow speed diesel container ships in the 16,000 KW power range. However, they believe that the same arrangement can be applied up to approximately 20,000 KW. The original ship design was not developed to incorporate unitization, therefore the full benefit of the concept was not realized.

It appeared that Thyssen did not use parametric design for their unitization program, but rather employed a custom design process. However, Thyssen stated they are moving toward standardization with the intent of developing a generic set of machinery units. The unit structure and ship's hull structure of the design were designed completely independent of each other.

Additionally, the team evaluated current practices in their

own yard. NASSCO has been constructing large integrated machinery units for all ship contracts since 1986. Most recently, the Sealift New Construction Program has made maximum use of integrated machinery units. Fig. 2 shows a lower-level seawater cooling unit. An entire set of lower engine room units were built side by side, completely outfitted, and then erected onboard and bolted together. These units, however, are ship specific and cannot be reused from one ship class to the next.

Fig. 2 NASSCO SLNC Lower-Level Seawater Unit

The team also investigated the practices of Kawasaki Heavy Industries (KHI) of Japan. KHI does not utilize unitization to the extent that this study proposes but they do make use of what is referred to as system units. The system units incorporate the concept of standard system design at the design level, but not at the production level. They do not unitize at the production level for the following reason: The additional steel required for unitization increases material cost, adds weight, and decreases fuel efficiency. However, KHI does envision that standard machinery units provide the following advantages:

- Reduced overall production cost
- Reduced system and detail design cost

Land-Based Industrial Plant Design and Construction Practices

The team visited two facilities assembled using unitized construction techniques. Research focused on the design and construction practices of one company, Raytheon Engineers and Constructors. Additionally, the team visited the company's engineering and fabrication facility.

Design. For each new project a team is assembled comprised of the customer, multi-discipline engineers, constructors and fabricators. The team conducts a multi-level review and development process. Concurrent engineering and design occurs throughout these levels, beginning with process sizing, major equipment sizing, and plant layout to satisfy process and unitization needs. Detail design takes place at later stages of development.

Guided by a set of "expert rules" the units are parametrically designed based on plant size and several other considerations including:

- Equipment arrangement requirements
- Process requirements
- Fabrication technique requirements
- Lifting or rigging requirements
- Transportation requirements

Land-based industrial plant and standard machinery units are comprised of two groups: *process specific units*, which are built custom for each specific application, and *utility/support units* which are standard. The ratio between the quantity of custom and standard units varies significantly based on the type of project.

Industry standards are used during the design phase, but often vary based on national and local codes, customer requirements, design requirements, and economics. These industry standards are generic, and are not developed specifically for design and fabrication of machinery units. Upon completion of each machinery unit design, the completed drawings are placed in a library for possible use on future projects.

Fully outfitted machinery units typically consist of the following: a structural sub-base or foundation, machinery and electrical equipment, ventilation ducting, free standing tanks, equipment removal gear, associated piping, wireways, cable, and walking surfaces. Machinery units may incorporate the walls and ceiling of the associated building or structure. Electrical systems are incorporated into the unit design with full pre-wiring of all circuits, except on those systems designated as uninterruptable by code. Electrical connectors are used between units in lieu of hardwiring. Cold checks are performed at the unit outfit stage. Control rooms are designed and fabricated as fully outfitted machinery units. Storerooms, offices and other commercial type spaces are usually procured as units from specialty vendors.

Transportation to the erection site varies based on geographical location, and local restrictions. Alternate forms of transportation include truck, rail, and barge. All three methods are suitable for transport of units designed for shipboard application.

Construction. The assembly execution plan pre-designates staging assembly areas. Steel is fully erected up to the top elevation which is left open for equipment and piping erection. Wide flange beams, channel, rectangular and square tubing are used in the fabrication of the unit structure. Selection is dictated by structural and economic requirements. Walkways are of diamond plate or open grating, bolted, welded or saddle clipped, made in pre-assembled galleries and installed on the unit. The unit structure is usually of welded construction accomplished in the shop, with bolted connections for field construction.

The construction process follows a logical sequence of steel assembly, paint, equipment installation, pipe assembly, instrumentation and electrical installation, and test. Units are usually assembled individually unless process or testing requirements require integration. Pipe make-up pieces between units are not necessary due to the close tolerances attainable using standard framing patterns, assembly jigs, and manual and electronic measuring devices.

Benchmarking Results

Benchmarking both shipbuilding and land-based construction and unitization practices revealed that the advantages of unitization far outweighed the disadvantages. Although the rationale for unitization varied slightly among the applications, the following advantages were manifest in both:

- Reduced overall construction schedule
- Faster activation of plant upon construction completion
- Reduced overall production cost
- Reduced system and detail design cost

- Improved quality and safety

MACHINERY UNIT DESIGN STRATEGY

The design strategy employed by the team utilized parametric analysis to systematically evaluate the key product variables and select a single or family of similar solutions. The resulting parametric design guidelines were organized in the following six separate but related areas:

- Systems Design
- Arrangement Design
- Structural Unit Design
- Machinery Unit Design
- Engine Room Structural Design
- Build Strategy

The analysis and development of these guidelines is described in the following sections.

SYSTEMS DESIGN

The rationale behind the parametric design for engine room systems is part of an ongoing effort to improve engineering, design and production techniques throughout the U.S. shipbuilding industry. The shipboard system designs described in this paper are meant to be representative of generic systems applicable to a broad category of ship types over a relatively large installed horsepower range. The objective behind this system design approach is two-fold:

- First, the parametric system design selectively reduces the number of system components to the minimum required for safe and efficient operation of the vessel.
- Second, the concept focuses on identifying systems which are common to most types of vessels presently under consideration by worldwide ship owners and operators.

The selected systems are initially developed to suit a vessel of mid-range size and powering. By utilizing parametric design concepts, the componentry identified for these selected systems is sized accordingly for vessels of greater or lesser size and powering.

A comprehensive study of shipboard system diagrams from leading shipbuilding companies such as Kawasaki Heavy Industries (KHI), and leading engine manufacturers such as Burmeister and Wain (B&W), and Sulzer formed the basis for system design and componentry selection. Information regarding system design and component selection is incorporated into the standard system diagrams; consequently, these system diagrams are representative of current industry
standards.

Traditional Approach

Traditionally, US shipbuilders have considered the system design of each new vessel as an individual effort. This approach has required significant labor hours for the development of customized shipboard systems for each new design. The parametric design concept is a method by which this task can be minimized. The parametric design concept views each vessel as part of a larger effort inclusive of many different types and sizes of vessels, not as an individual effort.

The initial design of a standard system which is generic to a wide cross-section of vessel types and sizes may represent an increased effort over a single ship design. However, the long-range benefits of a common design are apparent in improved quality and

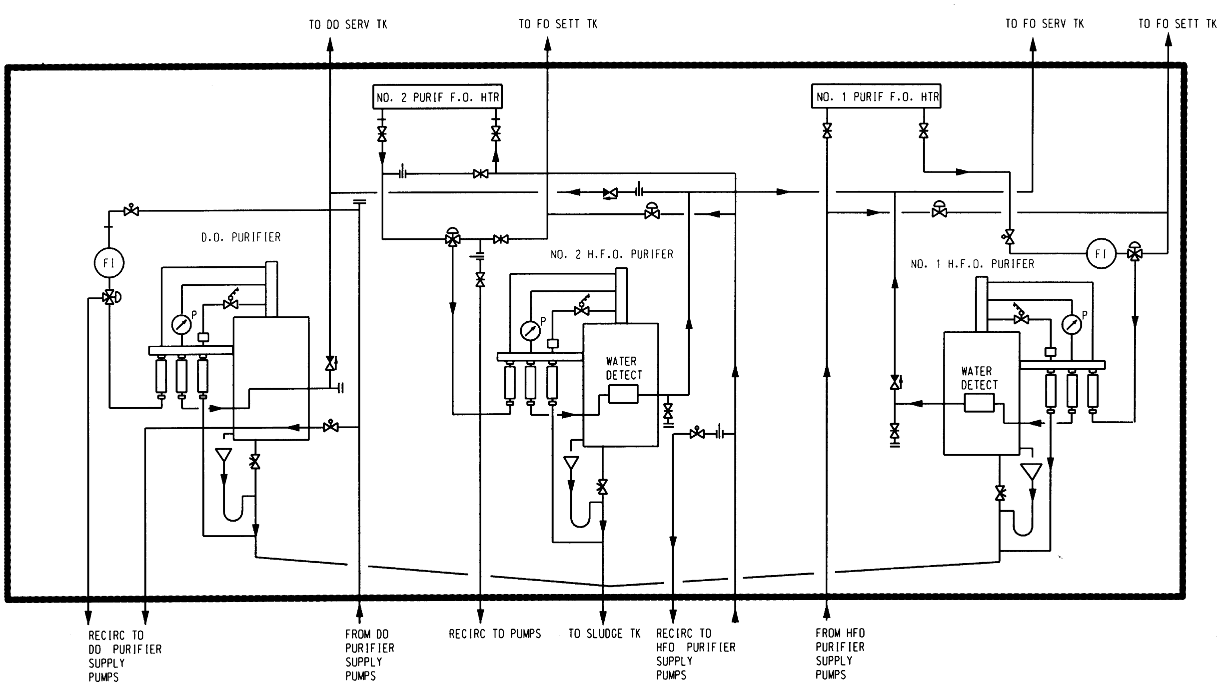

Fig. 3 Fuel Oil Purificaton System Unit Diagram

reduced engineering, design, and production costs over the span of several contracts. The parametric approach augments benefits derived from a standardized multiple ship approach. These advantages can be fully realized in construction of series-built standard designs or vessels of conventional features.

Parametric Approach

To successfully implement a parametric design concept and compete in a global marketplace the U.S. shipbuilding industry must strive to accommodate customer needs. The concept introduced by this paper is unique in that it encompasses a majority of engine room systems. It is critical that both owners and shipbuilders agree on standard system architecture common to several vessel types and sizes. Although these selected systems must maintain a standard design, it is also important that the systems be flexible enough to accommodate customer unique requirements. The system designs suggested in this paper allow for such variations based on owner's desires.

Regarding the worldwide market for ship construction, the project focuses on five ship types: *Crude Oil Carriers, Product Carriers, Container Ships, RO/RO Vessels, and Bulk Carriers.* This decision was made in anticipation of the types of ships that may be ordered by the world market in the near future.

Integration of the parametric design concept first required identification of those systems that are common throughout this range of ship types. Data collection gained through investigation of previously constructed U.S. and foreign vessels provided the basis for a matrix identifying principle engine room systems. The relationship of these systems to various ship types was determined with regard to pertinent characteristics.

System Selection

From this matrix 23 systems were selected for further development based on their commonality across multiple ship types. Standard system diagrams were developed for these systems.

The major equipment of the selected systems was then compared to ships previously constructed to consider possibilities for componentry reduction and simplification of system architecture. The major components of these systems were then arranged into individual system units based on a mid-size vessel. The team developed a second matrix to identify the relationships between the units and the principle engine room systems. Individual system unit diagrams were created depicting major componentry and the associated system piping. A representative sample of these diagrams is presented as Fig. 3.

Distributive Electrical Systems

The team determined that by using a distributive system architecture for electrical power and automation, system cable footage and routing was simplified. Using this type of architecture, large electrical components such as: group controllers, power panels, and data acquisition units were systematically distributed throughout the engine room. This approach provided an increased level of local control and remote alarm monitoring, reduced cabling requirements, and increased pre-outfit potential when compared to a centralized system.

System Unit Selection

A representative sample of six principle units were selected for further development and component selection. These six units were:

- Fuel Oil, Diesel Oil and Lube Oil Fill and Transfer Unit
- Main Engine and Diesel Generator Fuel Oil Heating and Service Unit
- Fuel Oil Purification Unit
- Lube Oil Purification Unit
- Fresh Water Generation Unit
- Fresh Water Transfer and Potable Water Unit

Initial equipment selection for these units was performed using a mid-size vessel as the model. The design team determined that natural size/model break points generally do not exist for component selection throughout the size and horsepower ranges for these vessels. Through analysis it was decided that a division of three equal groups would be sufficient to size equipment for most major systems.

These three divisions were based on main engine horsepower, crew size, or cargo requirements, depending on the function of the respective system. Twenty main engines were selected from two major engine manufacturers (B&W and Sulzer). Selection of these engines, covering the horsepower range from 10,000 Hp to 50,000 Hp, was prerequisite to auxiliary component selection.

Equipment Selection

Prior to equipment selection, vendor information on major components was evaluated and a library was created to ensure that only currently manufactured components would be selected.

Equipment and componentry was selected using generally accepted system design guidelines. In all cases, equipment was selected from standard models of two or more manufacturers. Ideally, in practice manufacturers' components would be pre-approved by the shipyard and registered as "standard equipment" to facilitate the selection process. The associated components were then scaled up or down to accommodate the parametric sizing of the system units.

Intended Use

The system units developed for this paper define the connectivity requirements between principle systems. The requirements of the system units also define an affinity for interrelated components and systems. The engine room arrangement templates and structural designs which follow are based on these system unit diagrams, and are systematically arranged to provide design efficiency.

ARRANGEMENT DESIGN

The team's approach to arrangement design is meant to govern the final configuration of the engine room by controlling the parameters that influence design. With this approach, most high-level strategic decisions are made prior to the individual designers' commencement of arrangement design. Furthermore, the use of parametric methodology ensures that arrangement designs are not unique and that the same basic conceptual arrangement is em-

ployed throughout various ship types.

Several problems arise when using the traditional approach to engine room layout:

- Arrangement design for any given vessel is generally treated as unique. This increases design time and increases the possibility for design inconsistencies from vessel to vessel.
- Individual designers are responsible for both high-level and detail decisions regarding arrangement. As the designers and their expertise change, then so does the arrangement.
- Constraints imposed by structural scantlings often make it difficult to design an efficient arrangement. These constraints normally dictate the designers' flexibility with regard to arrangement. Designers must consider structure such as bulkheads and stanchions within the engine room space, and work around these obstacles.
- Distributive system routing, access requirements, and lifting requirements are often considered only as an after-thought due to the inherent complexity of equipment arrangement. This complexity is further amplified by imposed structural constraints. Late consideration of these important design factors often results in a less than efficient design.

Parametric Approach

The parametric approach for engine room arrangement consists of decisions made on two distinct levels. High-level strategic decisions consider all variables in an attempt to reduce variation, and secondary decisions subsequently follow to minimize variation at the detail level.

Ideally, ships' lines and approximate engine room locations for a given vessel type are considered the primary fixed constraints for higher level analysis. This rule provides flexibility to determine an ideal engine room model for a given vessel type.

The goal of the team was to define a family of ideal models for engine room arrangements within the array of vessel types under consideration. An ideal engine room model requires an analysis of the relationship between major principle systems and the connectivity requirements of their distributive systems. The previously completed parametric analysis of systems provided a powerful tool to define the necessary relationship between the major principle systems.

Results Achieved

Five engine room arrangement templates were developed. Fig. 4 is a representative sample. These models are based on the five ship types previously selected, and the grouping of major systems resulting from the parametric analysis of systems. The templates represent ideal arrangements for engine rooms within the ship types under consideration. Although five very distinct templates were developed, one for each specific vessel type, it should be noted that all templates bare similarities to each other, based on the optimum location of major systems.

Most systems have requirements to be in a certain geographical area within the engine room in support of system functionality and efficiency. High-level decisions include: grouping all fuel and lube oil systems together, grouping all water cooled systems together, and keeping the Engineer's Operating Station close to the generators and as high in the engine room as possible. Such decisions reduce the requirements for distributive systems, and minimize interference of systems. Since the principle systems considered exist on most every ship type, the grouping of machinery units remains virtually unchanged.

Using templates as a basis for engine room arrangement provides the following benefits:

- Designers are provided high-level guidance. Such guidance leads to a common goal of efficiency in arrangement design.
- Engineering management, utilizing these templates, can incorporate and manage high-level decisions to control the outcome of the design process.
- The arrangement design is repeatable for a given vessel type and size, as well as for vessels of other types and sizes.
- Proper utilization of the templates will not only produce a highly efficient design, but will also reduce design time.
- Provides a common starting point for a concurrent engineering effort.

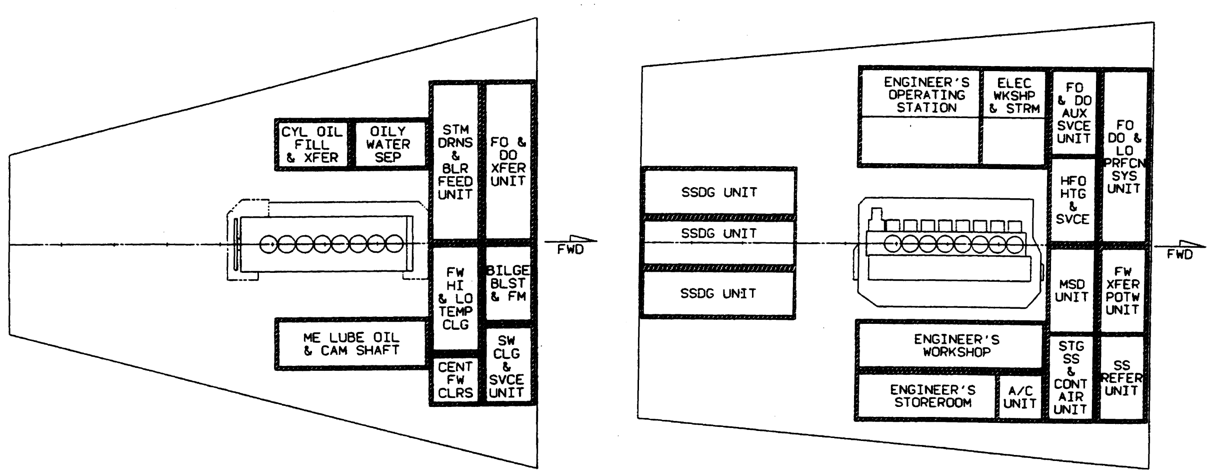

Fig. 4 Arrangement Template: Engine Room Aft, RO/RO with Low Head Room

Intended Use

The templates outlined by this paper are intended to equip engineering managers with a powerful tool to quickly select an arrangement strategy and make initial design decisions. The templates also enable management to effectively communicate their decisions to design engineers with a high degree of confidence that progress can be controlled with minimum effort and re-direction.

Strategies for distributive systems and distributive system lanes can easily be outlined. Pipeways, electrical wireways, and vent runs can be identified, evaluated, and selected. In addition to distributive system routing, access, equipment removal, and lifting requirements can also be considered and identified at this stage. Experience has shown that early implementation of the above strategy will improve design efficiency will provide for reduced cost and schedule during production.

STRUCTURAL UNIT DESIGN

The team developed a design strategy and guidelines for standard engine room structural units that can be used in a wide range of vessel types and sizes using a parametric approach. Engine room configuration using parametric design calls for a standard building block, which is defined as the structural unit.

Ideally, in order to remove the adverse effects of the engine room structure upon the framework of the structural units, it is necessary to uncouple the units from the main hull structure of the engine room. If this is not possible it is then necessary to include the effects of primary hull loads when designing structural units. The structural unit is built within the design parameters inherent to the internal structure of the unit, yet it still achieves the required effects on hull integrity and hull vibration.

Standardized Approach

The design for standard structural units outlined in this paper results in similar structural arrangements and systems across ship types regardless of the selected design team and their individual expertise. Subsequently, this approach will produce a high-level of commonality, thereby reducing design cycle time and costs associated with construction. By virtue of a standardized approach, the structural unit design is based on two parameters which vary little from ship to ship. These parameters are *loading* and *vibration*. Key variables such as ship type, size, speed, horsepower, engine room location, and engine room size have minimal effect on the structural unit parameters.

A standard engine room is considered as a two or three level structure comprised of multiple units arranged on each level constructed around the main engine. The number of units comprising each level will be discussed later in this paper. Using the five templates as previously described, an analysis was performed. This analysis considered; the relative size of the system unit arrangement, the available area within the engine room (engine room volume), and shipping constraints (if the structural unit were to be constructed in a facility outside of the shipyard). The analysis included vessels of varying breadths, using Panamax beam of 32.2m (106 ft) as a break point for structural unit sizing. The team concluded that a standard structural unit of 3m (10 ft) wide by 3m (10 ft) long by 3.6m (12 ft) high would be appropriate for all vessels below Panamax beam, while a standard structural unit of 3.6m (12 ft) wide by 3.6m (12 ft) long by 4m (13 ft) high would be required for vessels of Panamax beam and larger. A possible need for deviation from these standards was foreseen to accommodate SSDGs, large air receivers, or to conform to the main hull structure in certain areas of the engine room. In accordance with the five templates, these taller units would be located on the upper level so as not to interfere with units above.

Loading Criteria

The loading criteria was determined by evaluating the weight and geometrical features of typical machinery units and equipment. For a standard structural unit, three distributed loading categories were selected. The structural unit strength and vibration adequacy were verified using structural engineering principles and Finite Element Analysis (FEA).

Lower-Level Units. Units designated for installation on the lower engine room levels are designed for system unit loads of 1220 Kg/m² (250 Lb/ft²). The girder members and grid members are designed for these loads and appropriate vibration levels. The vertical members are designed not only to support their own unit load but also to support the load transmitted from the levels above.

Middle and Upper Level Units. The mid and upper level units, which contain auxiliary machinery, are designed for a 1220 Kg/m² (250 Lb/ft²) loading. The upper level units used for store rooms and control rooms are designed for a 732 Kg/m² (150 Lb/ft²) loading. All units are designed for the appropriate vibration levels. The vertical members of these units are also designed to provide support for the load transmitted from the levels above.

Upper Level Generator Units. The upper level generator units are similar to the upper and mid-level auxiliary units in geometric configuration, but are designed for 2197 Kg/m² (450 Lb/ft²). This design reflects loading from SSDGs and air compressor sets located on this level. The component framing members are of similar shape of the earlier two unit types but are heavier sections.

Vibration Criteria

In defining the vibration criteria, two sources of vibration excitation were considered: the propeller blade rate pulsation and the engine beat rate pulsation. In a vessel with an engine room aft configuration, the blade rate becomes the dominant limiting criteria. Conversely, in a vessel with an engine room located 2/3 aft, the energy content in blade rate pulsation is much lower and the engine beat rate becomes the dominant limiting criteria. The structural unit, as well as the multiple unit arrangements are designed to keep their natural frequency and even higher modal frequencies out of the frequency ranges of concern.

Structural Unit Configuration

The template for an engine room 2/3 aft container ship was selected for detailed analysis, and three representative structural unit detail arrangements were developed. All three of these structural units have the same structural configuration, but vary in overall dimensions and component scantling sizes.

Regarding construction, the following two variations of the basic structural unit configurations were analyzed:

- Longitudinal system
- Transverse system

The team concluded that transverse grid members were preferable for support of piping runs. Vertical members are kept continuous and longitudinal load carrying members (girder members) are inter-coastal between adjacent units comprising a multiple unit arrangement.

The framing members, or scantlings, for these structural units are very much dependent on the charateristics of the standard machinery unit which it incorporates. The horizontal members of the structural units are designed as I-beams or W-sections as shown in the AISC Steel Construction Manual. The vertical members are designed as I-beams, except in areas requiring mechanical connection to adjacent units. For this application the vertical members are designed as channels thereby forming an I-beam when mechanically joined to an adjacent unit with similar channel construction.

In standard machinery unit applications, adjacent units are mechanically joined using bolted construction. The structural units are arranged such that the vertical I-beam stanchions of a unit land on the vertical stanchions of the unit below. Ends of the vertical members are capped with flat plate pieces to ensure proper alignment and facilitate mechanical fastening to vertical members of adjoining units. Horizontal orientation of units is accomplished in such a way as to allow channels of adjacent units to align back to back or to have their flanges side by side to allow for mechanical fastening.

MACHINERY UNIT DESIGN

The machinery unit design arrangement selected by the team is based upon parametric analysis of the system designs, engine room arrangements, and structural unit design previously discussed. The integration of standard system units and selected individual components along with the ship's distributive systems onto standard structural unit building blocks creates the complete engine room arrangement. The use of parametric design strategies allows for standardization of such machinery units and their structural and system interfaces across the required range of ship types and sizes.

Parametric Approach

Parametric analysis of the machinery unit design was based upon the analysis described in preceding sections. The arrangement selected included standard locations of system units, walkways, equipment removal routes and monorails, pipelanes, cableways, and structural interfaces from unit to unit.

The team also performed structural unit size analysis for the arrangement of auxiliary system units, selected components, ship's distributed systems, and for machinery control and workshop spaces. The team's analysis concluded that standard structural units of 3m (10 ft) wide by 3.6m (12 ft) high are appropriate for all vessels below Panamax size, while structural units of 3.6m (12 ft) wide by 4m (13 ft) high are recommended for larger vessels.

System Unit Design

System unit design was based on analysis of the system unit diagrams previously developed. The analysis was performed to determine the optimum size and arrangement of each type of unit. System unit arrangement sketches were developed for nineteen system units based upon these arrangements and the connectivity requirements between the principle systems. 3-D system unit drawings were developed for the six systems identified in the system design section. A typical system unit is shown in Fig. 5.

The system unit designs include detail arrangements of the sub-bases, equipment, and systems incorporated on each system unit. The designs also include detail information on unit height and weight. Although not accomplished within the scope of the initial project, the long-term plan is to develop a family of parametrically sized units that cover the total range of system capacity. Many system units such as purifier skids are available from equipment vendors. It is envisioned that the shipyard would design and build the balance.

Standard Machinery Unit Design

The standard machinery design combines standard system units, selected individual components, ship's distributive systems, and a standard unit structural pattern to create a total engine room system that replaces conventional flats and distributed systems and components. The arrangement of typical machinery units was developed to test and evaluate the design concept. This evaluation considered the following: Human factors engineering, equipment maintenance and removal envelopes, simplified system routing and installation arrangements, standardized system unit locations, units to handle machinery control and workshop spaces, and standardized system interfaces from unit to unit. In certain cases such as the machinery control room, workshops, and store rooms, it is advantageous to use two machinery units, side by side, to form the space.

The arrangement of two standard machinery units forming

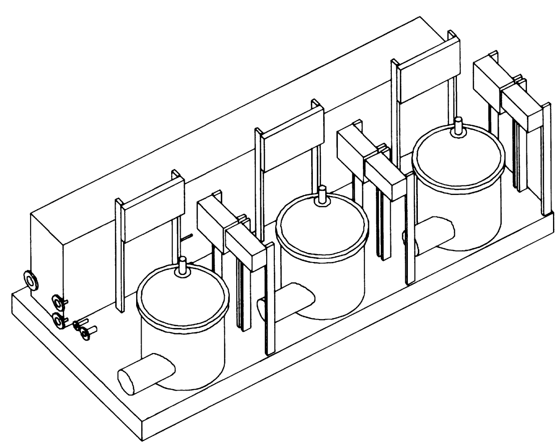

Fig. 5 Fuel Oil Purification System Unit

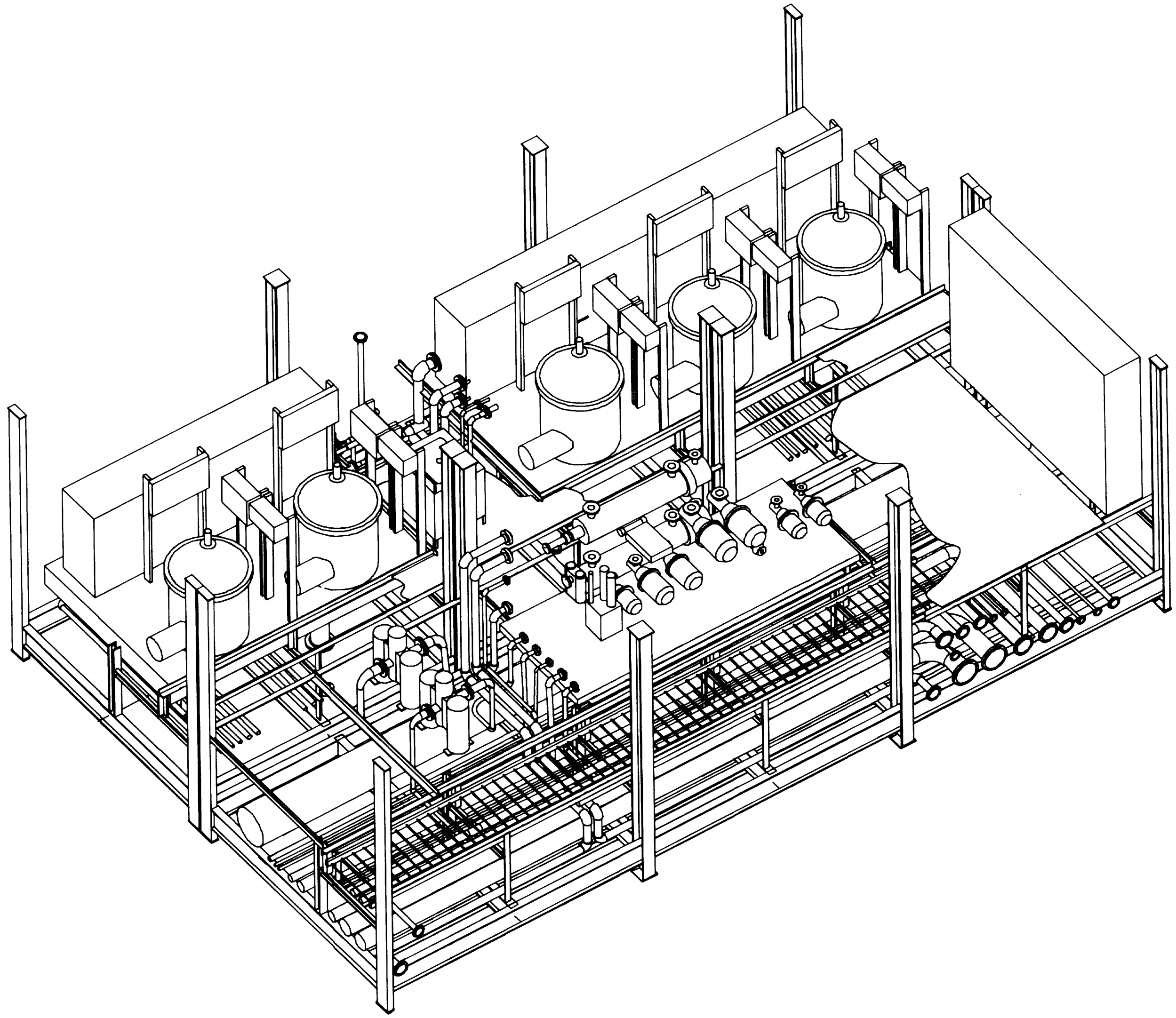

Fig. 6 Two Standard Machinery Units Containing LO, FO & DO Service & Purification System Units

the fuel and lube oil purification and service space is shown in Fig. 6. This figure shows the arrangement of system units, individual components, ship's distributive systems, and walkways within the machinery units.

Although not performed within the study, the long-term plan is to develop a complete library of standard machinery unit construction arrangements and details to support detail design. This would include the development of standard owner options such as modular bulkheads to support an enclosed purifier space.

45,000 BHP Baseline

Utilizing the system designs, system equipment, arrangement templates, structural units, and machinery unit designs previously described the design team performed an initial application of the standard machinery concept on a container ship with an engine room 2/3 aft. This design became known as the 45,000 BHP baseline, and it was key in working out and demonstrating many of the unit arrangement concepts.

Results Achieved

The system and machinery unit design guidelines and their initial application to the 45,000 BHP baseline demonstrate the feasibility of the modular engine room approach. Additionally, the initial design application on the baseline arrangement validates the benefits of the parametric approach described in previous sections.

The team anticipates that the development of system and machinery unit design guidelines may represent an increase in initial design manhour costs when compared to a traditional design effort. However, the team also determined that the availability and use of these design guidelines will facilitate the rapid completion of the design process with a commensurate increase in design quality. The potential cost savings of such a library of standards over the span of several ship contracts was observed at the Japanese shipyards and industrial sights benchmarked as part of this study.

ENGINE ROOM STRUCTURAL DESIGN

The development of parametric standards for engine room structural arrangement is required to ensure effective integration of unitized engine room structural units into the primary ship structure. As stated previously, the design of the engine room structural arrangement must be developed in such a way as to permit the uncoupling of the structural units from the main hull structure while achieving both hull and machinery system performance requirements. Important factors that must be considered are:

- Hull integrity
- Longitudinal strength
- Adequate stiffness and strength in way of main propulsion system installations
- Adequate and proper support for machinery system components and distributive systems within the engine room

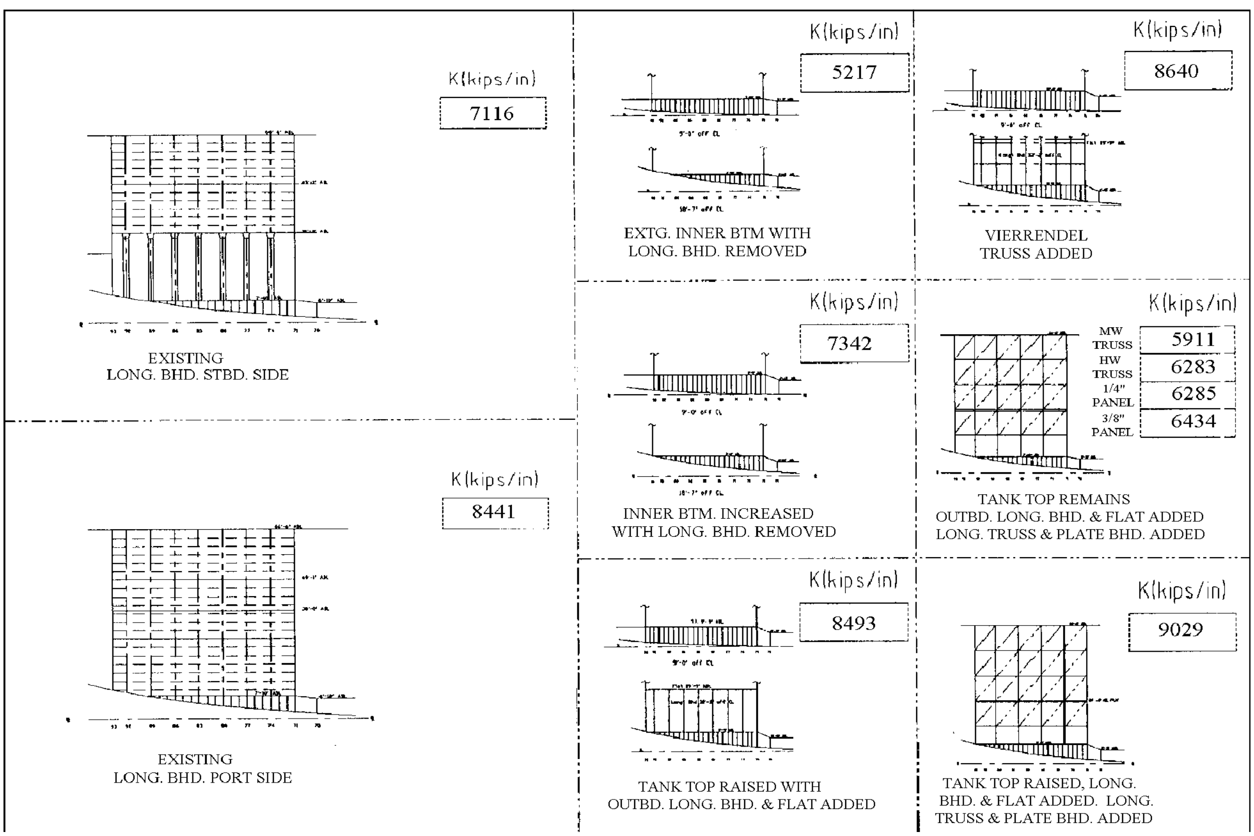

Fig. 7 Stifffness Comparison of Various Engine Room Structural Arrangements

- Proper support for superstructures that are located in way of the engine rooms and machinery space casings

A strategy was developed to compare alternative structural system concepts and to qualitatively establish target structural performance capabilities. This strategy was then implemented to select those approaches that were most cost effective, and that would enhance the development of optimum engine room structural units and a self supporting superstructure.

Application of Parametric Approach

To account for the key variables previously identified, a parametric design approach was established to qualitatively and quantitatively assess and develop alternative engine room structural arrangements. These alternative candidates were further evaluated to select a proper standard for engine room structural arrangement. Baseline stiffness characterizations were established for existing ship designs in order to provide a basis for evaluation.

Initial Concerns and Challenges

Issues of longitudinal strength and hull integrity were integral during the concept level of design development. In a traditional engine room structural arrangement double bottoms are supported by twin longitudinal bulkheads. These longitudinal bulkheads effectively reduce the span of the innerbottom in the transverse direction to 1/3 of its unsupported breadth. Thus the longitudinal bulkheads are an extremely important structural system component in providing adequate stiffness in way of main engine installations in the 2/3 aft engine room location. A challenge facing the team was to design an engine room structural arrangement to support standard machinery unit outfitting yet provide the required stiffness and strength.

A typical engine room structural arrangement employed in an engine room aft configuration utilizes similar innerbottom construction to that described for the 2/3 aft arrangement. However, the engine room aft arrangement usually does not have longitudinal bulkheads running down the length of the engine room. Generally, the engine room is narrower due to the inherent hull lines, and therefore the hull side shell, in a single shaft ship with a skeg, provides support for the innerbottom.

Alternative engine room structural systems that are more amenable to the unitized engine room design must achieve required stiffness characteristics in order to provide proper support to main engine and machinery within the engine room. Another challenge the team faced was to design an engine room structural system to allow the main engine foundations, unit structure, and superstructure to perform independently, or be self supporting, without negatively affecting each other.

Hull Integrity and Longitudinal Strength

The alternative engine room structural arrangements developed to provide support to the main engine and machinery units do not retain the traditional longitudinal bulkhead structure. Traditional structure is depicted in Fig. 7. The port bulkhead extends fully from the bottom shell to the weather deck, while the starboard bulkhead is solid from 9.7m (31’-8”) ABL to the weather deck with stanchions extending from the lower edge of the bulkhead down to the innerbottom.

Alternative Engine Room Structural Arrangements

Five alternative engine room structural arrangements were evaluated against a traditional design to determine the optimum engine room structural arrangement to support unitization. Alternative arrangements considered include the following:

- Traditional design with longitudinal bulkhead removed
- Deepened innerbottom design with no bulkheads
- Deepened innerbottom design with longitudinal bulkheads
- Deepened innerbottom design supported by outboard longitudinal bulkheads and flat designed to reduce the effective width of innerbottom
- Deepened innerbottom design with no bulkheads and an expanded engine room length

Validation of Alternative Arrangements

In order to validate the alternative engine room structural arrangements, the various configurations were modeled using FEA. First, more detailed plate models were constructed which characterized a typical prismatic shaped engine room of a Panamax containership. Three point loads were applied to the model located along the bottom longitudinal structure in line with the engine mounting bolts. Longitudinally, these loads were located at even intervals along the length of the engine room.

In order to quantify the stiffness of the engine room structural arrangement, an effective “k” value was calculated by dividing the sum of the vertical deflections of the structure at each of the applied loads by the sum of the applied loads. This “k” value is indicative of the vertical stiffness of the structural system and represents the relative ability of the system to match the vibrational resistance of the traditional configuration. Stiffness for the alternative configurations are provided in Fig. 7.

Engine Room Structure and Machinery Unit Interfaces

To provide proper support for the standard machinery units, the proposed alternative engine room structural systems will position the innerbottom structure directly under the individual unit structural stanchions. The transverse structure within the wing walls and the supporting structure on the transverse bulkheads will also be aligned with the unit framing. Parametric analyses and calculations were performed to determine the reaction loads imposed by the individual unit structures on the engine room supporting structure. The forces and moments applied at the unit/ship interface connections take into account variations in the unit structure weights, equipment and system weights, and appropriate acceleration loads.

The innerbottom structural framing system provides the basic foundation structure in way of the main engine. However, the standard machinery units must be designed to support the engine in the transverse directions by use of sway braces where required.

One benefit of unitized construction of standard machinery units is to facilitate rapid outfitting of the machinery space. Thus, the unit structure and engine room structural interface connections must be simply designed, yet able to sustain the induced forces applied to the connection. Adequate clearance in way of the unit's structural framework and attachment connections must be designed into the system to facilitate rapid installation of standard machinery units in the engine room.

Superstructure Structural Systems

Typical ship superstructure design practice assumes that the house and stack casing are supported by the primary ship structure found within the engine room. The use of longitudinal bulkheads below the superstructure create unsupported spans within the superstructure which are relatively short, therefore, flexibility and stress are not concerns. However, unitized engine room systems allow the elimination of longitudinal bulkheads within the engine room. Therefore, superstructure must meet standard strength and vibration criteria as a standalone structure. To determine the validity of the standalone superstructure, an FEA model of the proposed structure was developed to conclude if the strength and stiffness of such a structure meets standard criteria.

The FEA model which was developed incorporated the house sides and decks as well as the transverse bulkheads at each end of the house. The geometry and scantlings of the original superstructure FEA model were based on those of a container ship as previously indicated. The superstructure and bulkheads were modeled to represent unsupported members, spanning transversely between the wing tanks, and longitudinally the length of the engine room. The decks were modeled with appropriate scantlings and plating thickness.

The self-supporting superstructure design interface with the engine room structure requires that the longitudinal wing wall structure and fore and aft transverse bulkheads be utilized to support the superstructure. Girders and bulkheads within the superstructure must be designed to interface with weather deck structure. The goal of the superstructure design is to permit load out of the engine room with machinery units, followed by erection of the entire superstructure as a single grand block, closing off the engine room compartment. The design of the superstructure connection to the main hull will facilitate rapid integration of the superstructure yet satisfy requirements for strength, rigidity and tightness.

Results Achieved

The team concluded that innerbottom arrangements utilizing increased depth can provide stiffness comparable to the traditional arrangement. Thus, the traditional longitudinal bulkhead arrangement can be replaced by an alternative structural arrangement with a raised tank top and flat outboard.

Additionally, the team concluded that the longitudinal bulkheads within the engine room are not required to provide primary hull strength, rather they should be designed to absorb longitudinally induced loads from hull bending. With respect to build strategy, the removal of the longitudinal bulkheads facilitates installation of the standard machinery units and interface with the engine room structure. The 45,000 BHP baseline arrangement validated the feasibility of unitized engine room arrangements and reinforced the anticipated benefits.

BUILD STRATEGY

The intent of the build strategy is to provide a standard plan for the construction of ships' engine rooms using unitized construction. The primary focus is to provide a set of parametric guidelines for the arrangement, fabrication, construction and erection of such engine rooms. These guidelines identify how standard machinery units will be fabricated and utilized across a range of ship types and sizes. Engine room system routings, which are often part of the build strategy, have been previously addressed. The build strategy establishes a benchmark for unitized engine room construction, and provides a baseline for continued improvements as measured by reduced work content, cost and cycle time.

The primary objectives of the unitized engine room construction are to:

- Allow parallel construction of the ship's machinery plant and hull structure, therefore reducing overall ship construction schedules.
- Move the majority of the work involved with building and outfitting an engine room off the ship to the more efficient ground outfitting stage.
- Allow a higher level of completion and testing of the machinery systems prior to launch.

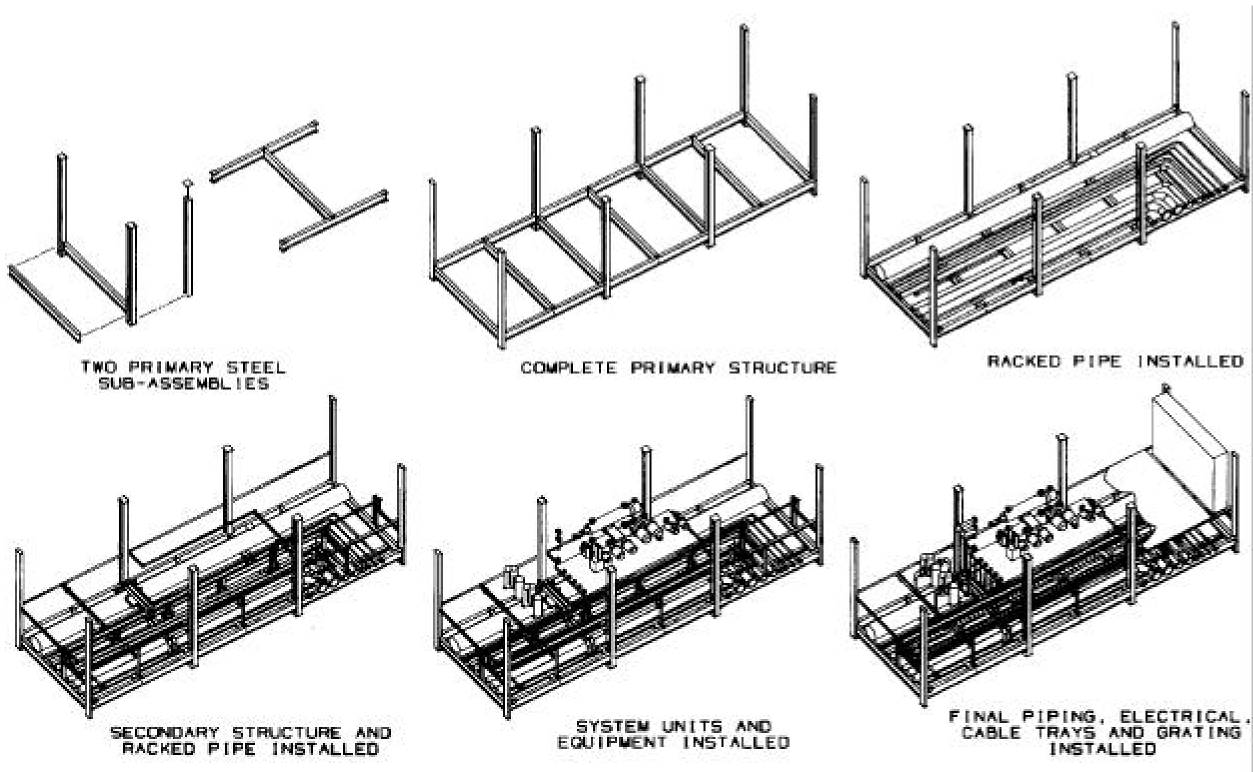

Fig. 8 Machinery Unit Assembly Process

- Give the shipbuilder the option of outsourcing part or all of the engine room construction if desired.

Standard Machinery Unit Assembly Process

The standard machinery unit design is based upon a standard repeating structural pattern and standard structural and system interfaces. Unit fabrication and assembly is designed for process flow lane assembly and is highly standardized.

Structural Unit Assembly. The structural unit design arrangement was developed to support:

- Standardization of parts, sub-assemblies, fabrication joints, and details making up the unitized structure
- Minimization of likely distortion through the assembly process
- Maximization of the use of jigs during fabrication to maintain accuracy
- Minimization of the number of pieces and joints fitted at later stages of fabrication

The structural unit assembly process makes use of two primary assemblies for construction of the standard structural unit. The pieces are all of standard length and are fabricated on a jig to maintain structural accuracy from assembly to assembly. The structural unit design can easily accept variations due to equipment weights and arrangements.

Machinery Unit Assembly. The standard machinery unit design arrangement was developed to support:

- Standardized arrangements, system interfaces, and construction details
- Standardized assembly sequence based upon a layered design concept with large piping and components landed using overhead cranes
- Workstation approach to unit assembly, outfit installation, and test
- Maximum outfit installation and test completion in the unit assembly stage

The machinery unit assembly process was developed to make the process as simple and efficient as possible. The unit primary steel structure is jigged during subassembly and assembly to maintain unit accuracy. Pipe is laid in rows on racks supported by the primary unit structure. Then secondary structure, additional pipe racks, and cable trays are installed prior to system unit and component installation. After main distributive systems have been installed, system units and individual equipment and auxiliaries are landed. This assembly strategy allows the units to be constructed in a layered process and allows the work packages to be scheduled in a logical and efficient sequence.

This machinery unit assembly process is shown in Fig. 8. After outfitting and testing, the standard machinery units can be further outfitted and tested at the grand unit phase.

Unit Hierarchy and Engine Room Construction

The machinery unit design approach utilizes a combination of ship unique pipe units, standard system units, standard machinery units, and selected individual components to complete the

assembly of the engine room. Where the shipyard has adequate lifting capacity, multiple standard units and pipe units can be combined into grand units. The hierarchy of such an engine room construction approach is illustrated in Fig. 9.

The aforementioned units may include, but not be limited to: auxiliary machinery, local and ship's distributed piping systems, foundations, decks, overheads, bulkheads, ventilation, tanks, hangers, ladders, padeyes, grating, lighting, local electrical cables, power panels, local and group controllers, and machinery automation components. Units are completed and tested to the maximum extent possible in the ground outfitting stage.

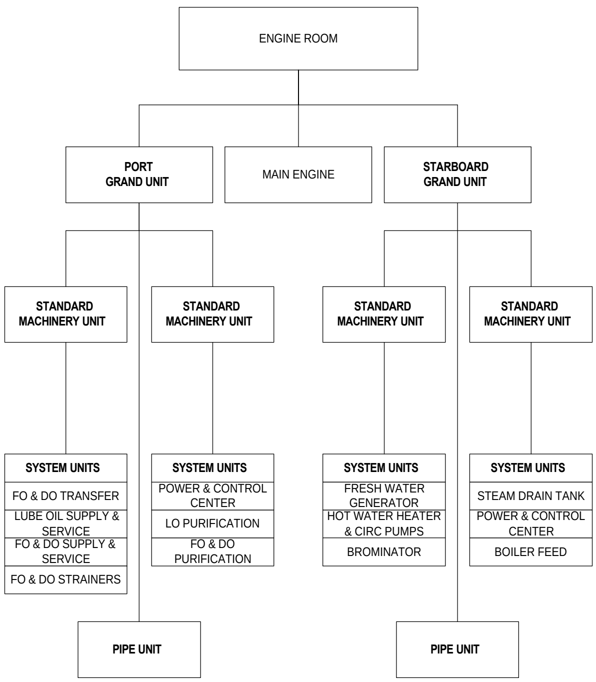

Fig. 9 Hierarchy of Engine Room Construction

Testing includes electrical cold checks and system hydrostatic testing. In some cases simulation can be run at the grand unit level to verify automated systems and interface operations. Finally, prior to erection, the units and grand units are completely painted and insulated.

The standard machinery unit engine room erection begins with the innerbottom and bottom shell blocks, engine room bulkheads, wing tanks, and box girders. The lower-level engine room units are then landed on the completed tank top. At this point engine erection will commence, followed approximately a week later by grand unit erection. The completion of engine erection and final grand unit erection will be concurrent to allow the engine room overhead blocks and house erection to be completed prior to launch.

Accuracy Control. Accuracy control is extremely important to the success of the unitization project. Ideally, unit steel fabrication, outfitting, grand unit assembly, and erection are done utilizing neat joints. To accomplish this level of quality control a reliable accuracy control program is imperative. To this end, the design of the standard machinery units focused on the following key concepts:

- The unit primary steel structure is constructed of simple, repeatable subassemblies.
- The unit primary steel structure subassemblies are fabricated on assembly jigs. Weld shrinkage is consistent and well defined due to the use of standard arrangements and joint details.
- The unit primary steel structure is assembled on fabrication jigs to ensure repeatable accurate structures from unit to unit.
- The standard machinery units will be outfitted and joined at the grand unit stage using fabrication jigs throughout the process to maintain dimensional accuracy.
- The standard machinery units will be outfitted using master reference lines to prevent errors normally encountered with stackable tolerances.

Rigging and Transportation. One of the factors considered in the design of the standard machinery units was to ensure the ability to outsource unit construction if the shipyard desired. A detailed study of transportation including truck, rail, and barge was conducted to determine the design constraints required. This study supported the selection of structural unit sizes previously described. After evaluation, it was determined that the static, dynamic, and vibrational loads imposed by shipboard design conditions far exceed any loads that would be imposed in the transportation of units.

An additional factor considered in the structural unit design was its ability to resist racking during lifting in either a single or multiple height configuration. The structural unit design selected is highly repetitive, thus promoting the use of standard lifting frames. These frames can be made in multiple sections, each section capable of connecting to a standard machinery unit. When the units are joined side by side or end to end, multiple sections of the lifting frame can be connected and used to accomplish the lift without distortion.

SHIP-SPECIFIC APPLICATION

The ship specific application of the standard machinery unit concept was included as the final project task of the ERAM portion of the Navy's Mid-Term Sealift Technology Development Program. The ERAM project team, assembled in 1995, was tasked with developing and applying an Integrated Product and Process Development (IPPD) design approach to concurrent engineering for the specific application of engine room arrangement, conceptual design, and integrated 3-D product modeling.

ERAM Team and Team Objectives

The ERAM team consisted of representatives from participating U.S. shipyards, foreign shipyards, owner/operators, engine manufacturers, government agencies, design agents and support personnel. The team is cross functional, co-located, and has been professionally trained. The ERAM team objectives were as follows:

- Provide a forum for U.S. shipbuilders to present views and needs for product and process design.
- Within 12 months develop a process for marine industry use to design internationally competitive commercial ships.

- Within 24-months demonstrate the process by designing four "World Class" engine room arrangements.
- Achieve customer-focus and buy-in of product design (4 engine room arrangements).
- Achieve U.S. shipbuilding industry-focus and buy-in of process design.
- Establish baseline commercial ship engine room designs for evaluation of future government initiated change.
- Document both the product and process design with rationale for use and future refinement by other users.

Project Approach

After NASSCO had developed the standard machinery unit concept a workshop was presented to the ERAM team and steering committee to provide developmental information on the parametric approach and an understanding as to how these solutions were to be applied. The approach that was chosen by the ERAM team consisted of selecting a previous iteration from the ERAM project, Slow Speed Diesel #1 (SSD #1), as the baseline design for applying the standard machinery unit concept. This new iteration would become the Slow Speed Diesel #3 (SSD #3) design. The results were then evaluated in the business evaluation task.

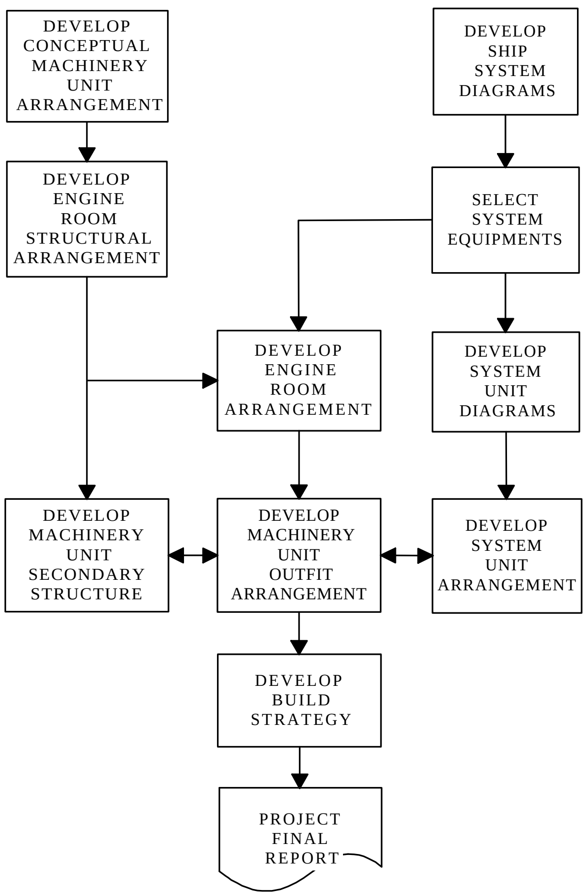

Fig. 10 Standard Machinery Unit Design Process

Slow Speed Diesel #3 Characteristics

The vessel characteristics of the SSD #3 were derived from the MARAD PD337 enhanced cargo ship design, a combination RO/RO container ship. They are as follows:

- Length overall - 200m (656 ft)
- Molded beam - 32.2m (105.62 ft)
- Molded depth - 18.0m (59 ft)
- Design draft - 9.15m (30 ft)
- Design displacement - 36,700 tons
- Ship service speed - 20 knots
- Main engine - MAN B&W 7S70MC slow speed diesel, 22500 BHP at 91rpm

Design Process

The standard machinery unit design application process is shown in Fig. 10. This high-level process flow chart shows how to effectively integrate the standard machinery unit concept in the design process. However, it should be noted that this process is a concurrent engineering approach, and that several process steps are being applied in parallel.

SSD #3 Fixed Parameters. Several of the existing parameters from the SSD #1 design were retained to ensure focus of the SSD #3 design iteration on the standard machinery concept application. This process ensured that the business evaluation was an accurate and useful tool. These fixed parameters included: equipment selection, a centerline stack, heat load requirements, high and low seachests with a sea pipe, and the selection of submerged main engine lube oil pumps. A standard machinery unit size of 3.6m x 3.6m x 4.0m (12ft x 12ft x 13ft) was selected based on a metric equivalent of the parametric approach recommended for this specific vessel.

Structural Interface. Once a conceptual standard machinery unit arrangement had been identified that would optimize the engine room configuration, an approach to integrate the ship's structure with that of the machinery unit's was agreed upon. The rationale behind this approach was to derive a structural system with a stiffness value equal to the original SSD #1 design. The removal of several internal tanks along with longitudinal bulkheads in way of the machinery units made for a very soft hull structure. Several options were evaluated, including the "coupling" of machinery units at 5m (16.4 ft) from centerline port and starboard to increase the stiffness. However, the final solution was the selection of a partial span longitudinal bulkhead at 5m (16.4 ft) off centerline, port and starboard. This part span bulkhead provided the necessary stiffness while still allowing an open architecture for easy loading of machinery units, particularly at the forward end of the engine room.

Systems Design. Development of ship specific system diagrams used SSD #1 as a baseline. The parametric approach was applied, including lessons learned from previous ERAM project designs. This ship specific solution included owner/operator options and addressed a life cycle cost of fifteen years. Comparison tables were created to document system deviations from the SSD #1 baseline and the standard machinery unit concept. The team

determined that any deviation from the parametric system approach would demonstrate the design flexibility of the approach. System equipment was selected from the SSD #1 base line, and new equipment was included as necessary to support the developed systems.

Engine Room Arrangement. The recommended approach was to apply a family of templates to develop an engine room arrangement. These templates gave the ERAM team a common starting point to develop three alternative options. The template family also identified, at the highest level: Access, equipment removal, and distributive system routes, thus simplifying the development of the three options. Analysis of the three options and the parametric templates identified improvements that could be made to the template family, the analysis tools, and ultimately the selected arrangement itself. The engine room arrangement specific to this ship application is shown in Fig. 11.

A key feature of the template application was the identification of locations of the engine control room, workshops, and storerooms. These locations revealed a large emphasis on engine room arrangement acceptability from a potential owner/operator standpoint. Location of system specific machinery units was generally

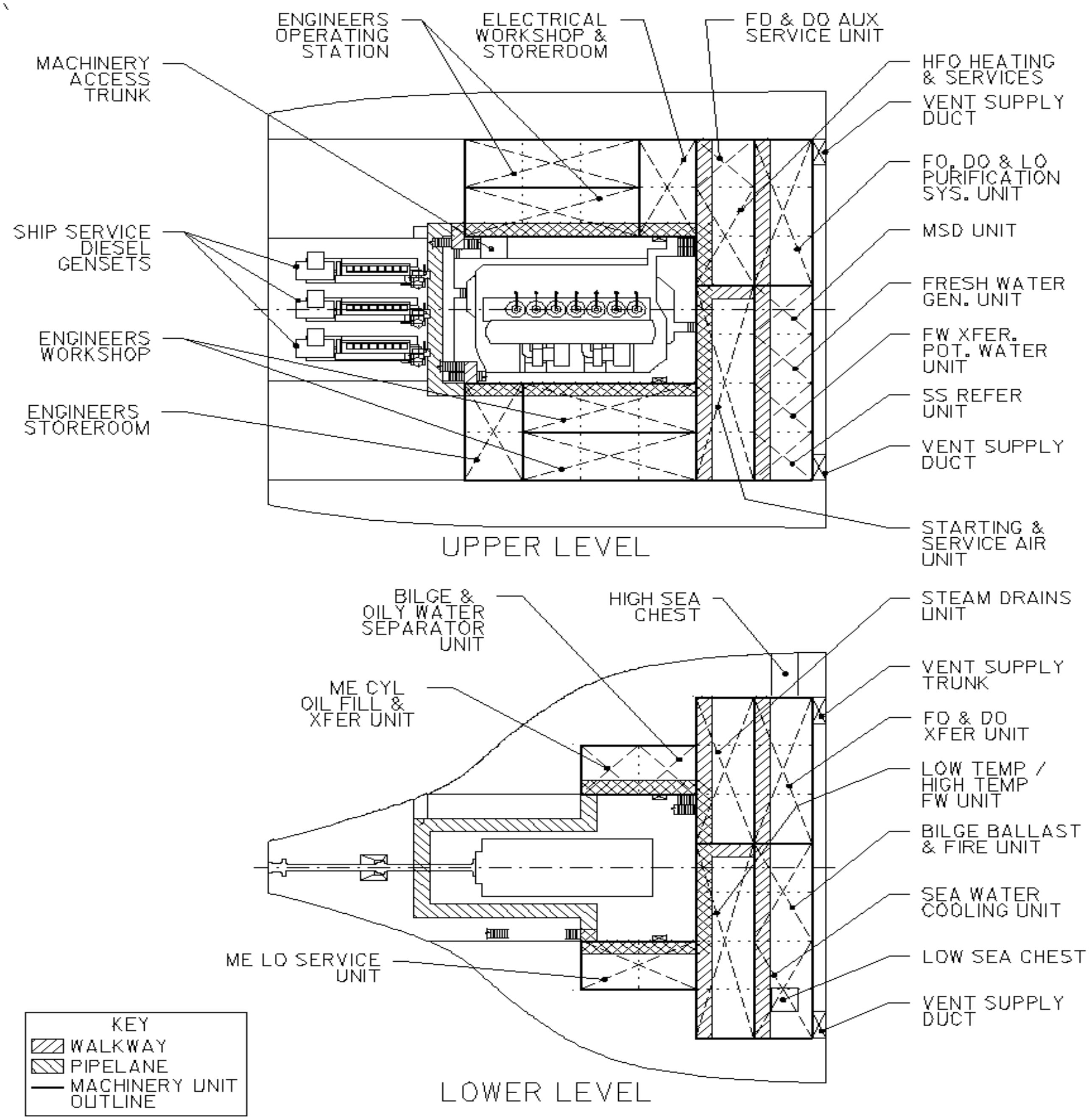

Fig. 11 Engine Room Arrangement SSD#3

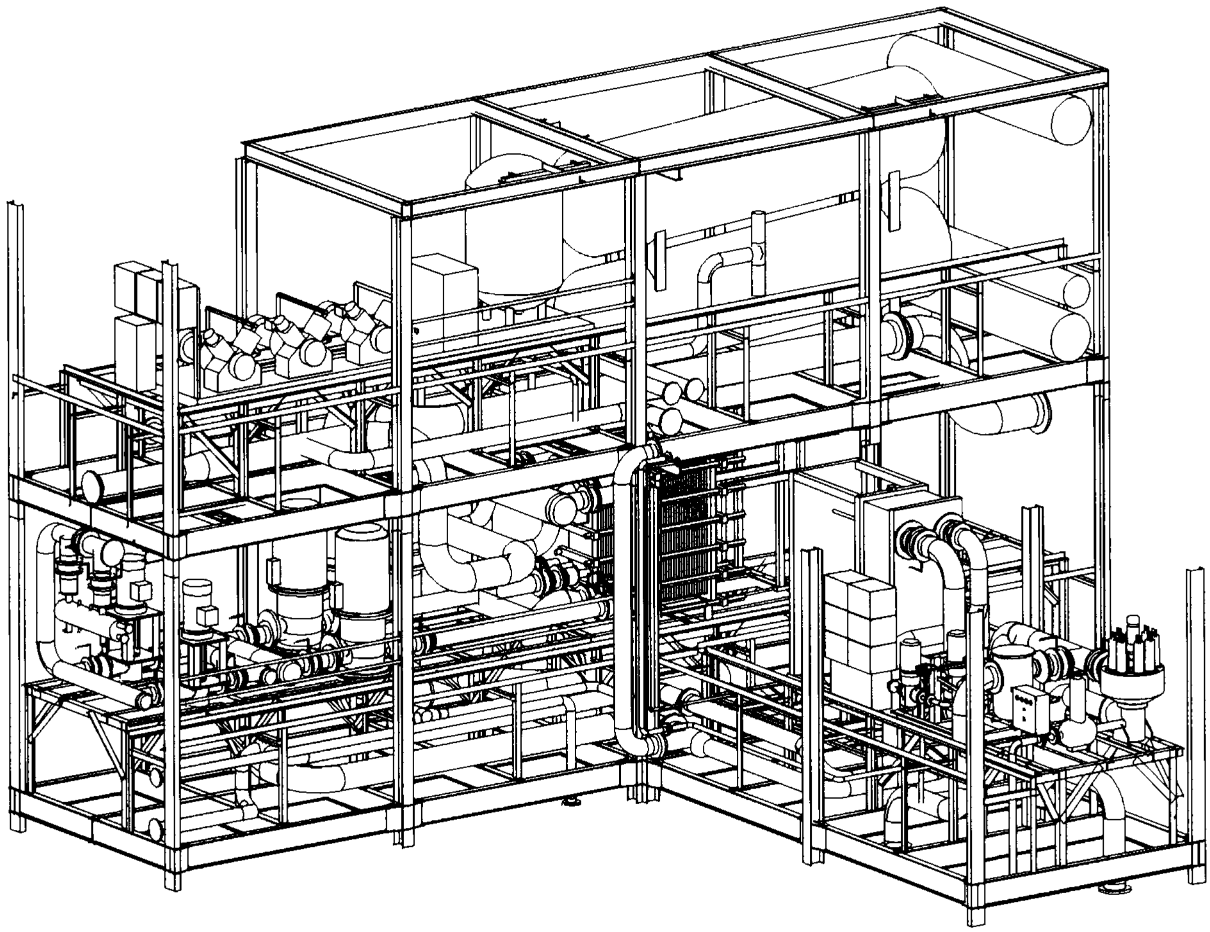

Fig. 12 Three Standard Machinery Units on SSD#3

easily agreed upon. Vent duct location to serve the engine room also created some concern as to the impact on potential cargo space, therefore, the forward vent ducts were relocated inside the machinery space.

Machinery Unit Design. The first step in the machinery unit design process was to develop system unit diagrams. These system units would in turn be located on the standard machinery units. System unit arrangements were then developed from these system unit diagrams. The use of vendor supplied system units was maximized where possible, however, some system units were designed in-house.

After personnel access arrangements were developed, the location of equipment within the machinery units was optimized. This included consideration of: Human factors engineering, simplified piping arrangements, and accommodation of maintenance and removal envelopes. A pipelane density study was performed to identify machinery unit through piping. Machinery unit secondary structure was developed and integrated to support system units and personal access walkways. The area beneath these walkways has been designated as the primary location for cableways and through piping. Segregating secondary structure from unit primary structure yielded a design that could be divorced for a parametric solution to equipment foundations. However, analysis for exceptionally heavy equipment indicated that in some cases additional primary structure is needed in the transverse direction due to the loading from roll accelerations. Additionally, structure was added to the machinery units located on the upper level to cap the top of the unit and enable complete pre-outfitting prior to loading onboard.

Five standard machinery units were selected to be fully detailed by the ERAM team. They were: lube oil service unit, fresh water cooling unit, compressed air unit, steam drains unit, and seawater unit. A 3-D model of three of these machinery units is illustrated in Fig. 12. These units were selected to provide detailed proof of the concept in specific key areas and to compliment NASSCO's earlier product development.

Build Strategy. Three grand units were identified, centerline, port, and starboard to be pre-assembled and installed in the engine room. The large seawater main is intended to be installed at grand unit stage of construction. A total of twenty three system units are contained within the seventeen standard machinery units. These standard machinery units consists of either a two, three or four bay standard structural unit. The team determined that by increasing the levels of outfitting installation and testing, and maximizing pre-outfitting of

electrical power and automation systems, considerable cost and

schedule savings were to be realized. The parametric approach and ship specific application to the SSD #3 design also identified considerable schedule savings from contract award to start of fabrication, where material lead time is on the critical path.

Lessons Learned

Process. The parametric approach to the machinery unitization concept provided a "jump start" for the ERAM team to commence the SSD #3 design iteration. This systematic approach provided a technically sound foundation upon which the ERAM team built. The experience yielded positive feedback to both the ERAM team and the NASSCO machinery unit design team.

Parts of the developed process became iterative, specifically the detailed development of machinery unit design. Application of this concept allows packaging of both the system architecture and the design effort itself into manageable tasks.

The IPPD process that the ERAM team developed and practiced allowed the concept to develop at an accelerated rate. Applying a parametric approach to machinery unitization allowed a higher level of concurrent engineering than any of the previous engine room design iterations.

Product. Because an owner/operator had been included as the voice of the customer from the ERAM project inception, satisfying the customer had become a very important part of the ERAM project. Locations of control rooms and store rooms within an engine room may be representative of the types of problems potential shipyards could encounter when trying to implement the parametric approach from a series of standard templates with a specific customer requirement.

Improvements to the parametric family of templates that were identified during this design iteration have been included in the complete template range to retain commonality throughout the parametric approach.

Within the workshops and stores areas traditional deck plating contained within the machinery units was considered the best solution to allow customer flexibility in relocating equipment. This also provides containment of fluids within areas with traditional deck drains.

Specific owner/operator concerns over operation and maintenance were considered during the SSD #3 design. These concerns were mainly the ingress and egress of equipment and personnel, complicated by the addition of several vertical stanchions between the machinery unit areas. Vertical stanchions within the engine control room and workshop areas are not required on the upper levels, and may be removed to minimize this effect.

In general, owner/operator participation in the ERAM SSD #3 design process was very valuable and it identified several improvements to both the concept and the specific design.

BUSINESS ASSESSMENT

As part of the Standard Machinery Unit development project, a business assessment of potential cost and schedule impacts was accomplished by three U.S. shipyards (Avondale, Bath Iron Works, and NASSCO) assisted by the ERAM Team. In support of this analysis, the ERAM Team provided a detailed comparision of design weights and footage's. A summary of these design metrics is shown in Fig. 13. This data shows a significant reduction in pipe and cable footage, along with a small structural weight increase on SSD #3 relative to SSD #1. In addition, the participants were provided a complete design package for each of the ships being evaluated.

Metric	SSD #1	SSD #3
Steel		
ER Structure (Tons)	1,680	1,641
ER Unit/FDN (Tons)	64	151
Total	1,744	1,792
Pipe		
Spooled (Ft.)	10,334	9,629
Non-Spooled (Ft.)	7,750	7,221
Total	18,054	16,850
Vent		
Spooled (Ft.)	915	1,010
Cable		
Power (Ft.)	36,631	32,968
Automation (Ft.)	21,178	19,060
Lighting (Ft.)	10,000	9,000

Fig. 13 Design Metrics

As part of the assessment, the three shipyards developed an analysis of potential advanced outfit metrics as shown in Fig. 14. This analysis shows a marked increase in on-unit completion levels in all categories, with a corresponding decrease in onboard work scope for SSD #3 relative to SSD #1. It must be recognized that the ability to achieve these metrics will be dependent upon the shipyard's ability to effectively implement the unitization concept through design and planning, and to develop an integrated test program.

With respect to the maturity of the standard machinery unit design concept, the three shipyards agreed that the cost and schedule assessment would be developed on the assumption that the concept had been fully developed and that an initial family of parametric standards was available.

Cost Assessment

In developing the cost assessment, two shipyards estimated only the portion of the engine room designed with standard machinery units, while the third shipyard estimated the complete engine room. A synthesis of their estimates of the potential cost improvement for SSD #3 relative to SSD #1 is shown in Fig. 15. While the shipyards anticipate that the initial development of parametric design guidelines may represent an increase in design manhour cost in the short term, they all agreed that there were potential savings in the order of 50-60% in engineering and planning, 35-50% in production, and 15-20% in material procurement over a series of several ship contracts.

Metric	SSD #1			SSD #3		
	On Unit	On Board	On Block	On Unit	On Board	On Block
Mechanical Equipment (%)	65	25	10	85	10	5
Electrical Equipment (%)	10	75	15	85	10	5
Pipe (%)	15	70	15	70	25	5
Ventilation (%)	0	90	10	70	25	5
Cable						
Power (%)	15	30	55	70	5	25
Automation (%)	15	30	55	75	5	20
Lighting (%)	0	80	20	75	10	15
Test (%)	5	30	65	60	5	35

Fig. 14 Advanced Outfit Metrics

The principle factors supporting these savings in cost include:

- System design and arrangement standards
- Standard unit structure, arrangements and details
- Standard vendor equipment
- Reduced design work content
- Ability to subcontract unit design/production
- Flow lane construction of machinery units
- Reduced onboard installation and test work scope
- Reduced onboard construction and test schedule
- Reduced product and process variation

Schedule Assessment

In assessing the potential schedule improvement, an overall design and construction activity schedule was developed for conventional design and construction, SSD #1, and for a ship designed and constructed with standard machinery units, SSD #3. This evaluation was reviewed by the three shipyards and found to be representative. This analysis is summarized in Fig. 16. The comparison shows a lead ship schedule of 19 months for SSD #3 with unitized construction vs. a schedule of 24 months for SSD #1 with conventional construction. It should be noted that individual ship construction schedules using standard machinery unit technology will have to be developed on a case by case basis considering the ship type, size, and shipyard capacity available. The principle factors supporting these reductions in cycle time include:

- Reduced system and detail design time
- Reduced auxiliary equipment procurement time
- Reduced machinery unit assembly time
- Parallel steel and outfit construction leading to later installation of engine room outfit
- Increased preoutfit installation and test levels
- Reduced onboard construction and test schedule
- Reduced product and process variation

Cost	SSD #1 Baseline	Standard Machinery Unit Design		
		1st Ship	4th Ship	8th Ship
Engineering	100 %	80 - 100 %	50 - 65 %	40 - 50 %
Design	100 %	80 - 100 %	50 - 65 %	40 - 50 %
Planning	100 %	80 - 100 %	50 - 65 %	40 - 50 %
Production	100 %	80 - 90 %	65 - 75 %	50 - 65 %
Material *	100 %	90 - 95 %	85 - 90 %	80 - 85 %

* Material excludes Main Engine

Fig. 15 Projected Cost Comparison

Schedule Interval	SSD #1	SSD #3
CA - SF	11	8
SF - K	3	3
K - L	6	5
L - D	4	3
TOTAL (months)	24	19

Fig. 16 Projected Schedule Comparison

SUMMARY

A parametrically derived family of large, fully integrated standard machinery units that are applicable over a range of ship types and installed horsepower has been developed. Although the project described focused on commercial ship machinery spaces using slow speed diesel power plants from 10,000 to 50,000 BHP, the approach is applicable with modifications to other ship types, power plants, and power ranges.

This system includes a family of integrated standard machinery units that replace conventional engine room flats and distributed machinery systems and components. The design guide developed as part of this project includes a hierarchy of standard units, the selection of standard unit sizes and interfaces, parametric design guidelines for system design, engine room arrangement and engine room structural design, and machinery unit structural and outfitting design. The approach described incorporates best practices as observed in “World Class” marine and U.S. land-based industrial plant design and construction. The design selected is considered superior to other marine applications observed, and is fully supportive of the original project objectives.

The standard machinery unit system has been demonstrated on a ship-specific engine room design and the business impact has been assessed by three U.S. shipyards. The results of the business assessment with respect to overall cost and schedule improvement are shown in Fig. 15 and 16. The principle design, material procurement, and production productivity improvement factors are summarized in Fig. 17. While additional development is required to support full implementation, the work to date demonstrates that the approach is both technically feasible and that its application to shipbuilding will result in strategic reductions in total program cost and schedule.

Design	Material Procurement	Production
• System design standards • Arrangement standards • Equipment standards • Machinery unit standards • Parallel Steel and Outfit Design • Reduced work content ⇒ system architecture ⇒ arrangements ⇒ unit structure • Reduced product variation	• Equipment standards • Reduced work content • Simplified unit structure • Reduced product variation	• Reduced work content • Work-station construction of engine room outfit • Parallel steel and outfit construction • Ability to sub-contract unit design and/or construction • Reduced onboard installation and test • Reduced product and process variation

Fig. 17 Standard Machinery Unit Productivity Factors

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Low Cost Digital Image Photogrammetry

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ABSTRACT

A problem in modular shipbuilding is the lack of a reliable, low cost method of obtaining and utilizing dimensional control in 3D . Photogrammetry has been successfully used as a tool for this application, but because of the large number of systematic errors associated with film-based cameras, only very large shipyards are using this. Recently, developments in Charge Coupled Device (CCD) imaging arrays for cameras have allowed some success in applying photogrammetric techniques in dimensional control. Main stream photogrammetric software and hardware configurations have been expensive and complicated. Digital camera systems and computers were purchased and programmed to tie existing inexpensive software packages with Geometric Dilution of Control (GDOP) error propagation analysis, originally designed for topographic mapping, into a tool for production shipyard fabrication dimensional control.

NOMENCLATURE

CCD Charge-Coupled Device
GDOP Geometric Dilution of Precision

INTRODUCTION

A major shortcoming in the shipbuilding industry is the lack of a reliable method of obtaining three-dimensional measurements of complex parts during fabrication and fitting to other parts. Photogrammetry has been successfully used as a tool for this application, but because of the large number of systematic errors associated with film-based cameras, only very large shipyards are using it because of the complexity of the film-based problem.[1] The requirements have been for expensive and exotic photogrammetric instruments, expensive proprietary special-purpose software packages, heavy training requirements for a multi-disciplinary staff, etc.[2] Furthermore, film-based photogrammetric systems tend to be on the slow end of the spectrum of dimensional-control systems. For quick turn-around time for results back to the workers in the shipyard, film-based photogrammetry has not been effective.

Recently, developments in Charge Coupled Device (CCD) imaging arrays for cameras have allowed some success in applying photogrammetric techniques without film in dimensional control. Previously classified technology for high-resolution CCD arrays has become available on the open market, but the existing film-based software has still been quite expensive. Digital camera systems and computers were purchased and configured to tie existing inexpensive software packages with Geometric Dilution of Precision (GDOP) error propagation originally designed for topographic mapping into a tool for production shipyard fabrication dimensional control. The availability of GDOP is a critical distinction for photogrammetric software. Most photogrammetry packages, both in the public domain (free) as well as commercial, have only rudimentary indicators of adjustment quality (errors) and commonly give only root-mean-square (rms) values for the fit of object space control. PC GIANT© performs an error propagation analysis of the geometric dilution of precision for every point in an adjustment, including the unknown points being solved. The presentation of GDOP results in the form of eigenvectors/eigenvalues allows the shipyard analyst to inspect the accuracy of each and every individual point identified for fitting. Graphical screen plots of positional errors presented as ellipses are an easy check to verify consistency of results; blunders and large errors become instantly evident. GDOP allows for a constant and consistent quality check for accuracy control.

The Kodak ™ DCS 460 cameras (Figure 1) are the most expensive component of the system developed. Presently, the cameras cost approximately $29,000 each, plus an additional $10,000 to include all the requisite accessories (multiple lenses, radio remote-control, tripod, case, etc.). The reliability of the three cameras

Figure 1

has been flawless except for one faulty battery that was replaced within 24 hours. The cameras seem to be completely acceptable for heavy day-to-day use in a shipyard environment.

However, the software will cost less than $3,000 per seat. Total single system cost is under $35,000.

TEST APPLICATIONS

Five separate digital photogrammetry test applications were initiated (the first three were at Avondale Shipyards) consisting of a shell bolster model, a mid-body section, a plate-cutting shop and an "as-built" machinery site.

Shell Bolster Model. Photographs were taken of a scale model at a shipyard. Images were imported to the Desktop Mapping System (DMS ®) mensuration software. The GDOP error analysis results appeared good, but initial reaction by Avondale personnel indicated that discrepancies existed. It was discovered that the discrepancies were due to the poor identification of the pin-prick targets utilized.

Double Hull Mid-body Tanker Section. Plans were made to use the digital camera system in providing dimensional control after an existing ship stern was cut for later mating to a new mid-body section and bow. Results appear promising. Large (25 mm (1 in.)diameter) day glow targets were used in daylight at a distance of approximately 27 meters (88 feet) with complete success.

Plate Shop / Factory. There was concern at Avondale Shipyards about their numerically-controlled flame cutting tables with respect to differential movement of large steel plates (24 mm thick x 6 m x 18 m)(1-inch thick x 20ft x 60ft) being cut. The remote control three-camera system was ideally suited for such an investigation to determine how much movement exists and when and where it occurs. Three cameras were set up and exposures were shot at 10-minute intervals for 2 hours; the period required to cut the subject steel plate. The electronic flashes were quite adequate for the distances which were less than 60 m (200 ft), but the orientation of the target points (flat retro-reflective tape stickers) were at too shallow an angle to permit sufficient light to return to all of the cameras. The results were inconclusive because of camera exposures of the target points. Initial results of target design research can be improved upon by using magnets and ball-bearings painted with various retro-reflective materials.

As Built Industrial Site. Wink Engineering collaborated with respect to an industrial As Built experiment which demonstrated 6 mm accuracy easily achieved over 10 m. Retro-reflective targets were used indoors with a electronic flash. The GDOP indicates that 10 meters is not a limiting size.

Tugboat Hull Offsets. A project was to quickly determine the "as-built" hull offsets of a tugboat inside of a dry dock. The project was a success with only one-half day of field work. Retro-reflective targets were used in daylight with electronic flash. Accuracy achieved was 8 mm (1/3 – inch) in the X-Y plane (more or less parallel to the deck) and 6 mm (1/4 inch) in the Z component (vertical) for a vessel over 30 m (100 feet) long.

OBJECTIVE

The shipyard system is capable of being used in production demonstrations as well as serving as a model configuration of components easily assembled by individual shipyards throughout the United States. The primary objective is to provide a demonstrable system that consists of standard (state-of-the-art) hardware components, standard (state-of-the-art) software components, and a minimum of customizing. Nothing in this research is especially new in concept except that system costs have plummeted. Technology has progressed in PC-based image processing, PC-based photogrammetry and digital camera design. Old ideas that were extremely difficult to implement are now well within reach of any shipyard in need of reliable, high-volume dimensional control. The system is intended to demonstrate that a single technician (with one or two helpers) can provide near real-time 3D dimensional control in a production shipyard environment. By minimizing the use of drydock time, the competitiveness of U.S. shipyards can be enhanced with the most advanced CCD cameras available for unclassified applications.

METHODOLOGY

The accuracies stated herein are as reported by the photogrammetric solution through the rigorous least squares adjustment of observed parameters and the GDOP. A variance-covariance matrix for each set of parameters is determined from the inverse of the normal equation. This is then multiplied by the estimate of variance of unit weight. The standard deviation for each element is the square root of the diagonal terms of that matrix.

The Variance of Unit Weight may be estimated by the equation:

$$\sigma_o^2 = \frac{\Sigma(\mathbf{v_i} \quad \mathbf{w_i} \quad \mathbf{v_i})}{(\mathbf{n}-\mathbf{u})} \qquad (1)$$

where,

v_i	is the residual of the i^{th} observation,
w_i	is the weight,
n	is the number of observations,
u	is the number of 'unknowns' or 'solvable parameters', and
(n-u)	is the degrees of freedom.

In the photogrammetric problem the number (n) of observations is equal to the number of plate components; one for x and one for y, or two times the number of image points measured. Add to this the number of measurements for object space coordinates. One for each of the known components (X,Y,Z). Depending on the external source of information, camera station position (X_C ,Y_C,Z_C) and orientation elements azimuth, elevation, swing (α, h, s) as well; they can be added to the number of observations as six times the number of camera stations. Although these are considered as solvable parameters, they can also be treated as weighted observations if sufficient information is available.

The unknowns or solvable parameters (u) are the object space control positions. For each unique point in the adjustment, three unknowns are counted. Camera station position (X_c,Y_c,Z_c) and orientation elements (α,h,s) are commonly considered 'unknowns', giving rise to additional numbers of unknowns equal to six times the number of camera stations.

To summarize,

v = the output residual for each observation,
w = input weight which may be thought of as
1/σ2 for each observation,
n = total number of observations,
m = 2 * number of plate measurements.,
c = 1 for each object space component,
s = 6 * number of camera stations.

The six camera parameters are always treated as unknowns; however, depending on the external source of information, these may also be treated as weighted observations contributing to the number of direct weighted observation equations. When the weights of the direct observations are small, the camera parameters may be treated as completely free and no contribution is then made to the direct weighted observations.

p = 3 * number of points (X_G,Y_G,Z_G). Note: one, two or three of these components may have also been counted as observations under 'c'.

Again, the estimate of variance of unit weight is defined as the summation of the input weights (1/σ2) multiplied by the output residuals squared (v2). If all is perfect,

$$\frac{\Sigma\mathbf{v}^2}{\sigma^2} = (\mathbf{n}-\mathbf{u}) \qquad (2)$$

for all observations. This summation, when divided by the degrees of freedom (the number of observations minus the number of parameters) results in a value close to 1.00.

For a two-dimensional case,[3] we consider the bivariate normal distribution then for random error components only:

$$\left(\frac{\mathbf{x}}{\sigma_\mathbf{x}}\right) - 2\_(\mathbf{xover} \quad \sigma_\mathbf{x})\left(\frac{\mathbf{y}}{\sigma_\mathbf{y}}\right)^2 = (1-\_^2)\mathbf{c}^2 \qquad (3)$$

This represents a family of error ellipses centered on the origin of the X,Y coordinate system. When c = 1, this is the standard error ellipse. The size, shape and orientation of the standard error ellipse are governed by the distribution parameters σ_x, σ_y, and ϱ.

Six examples illustrating the effects of different combinations of error distribution parameters are shown in Figure 2

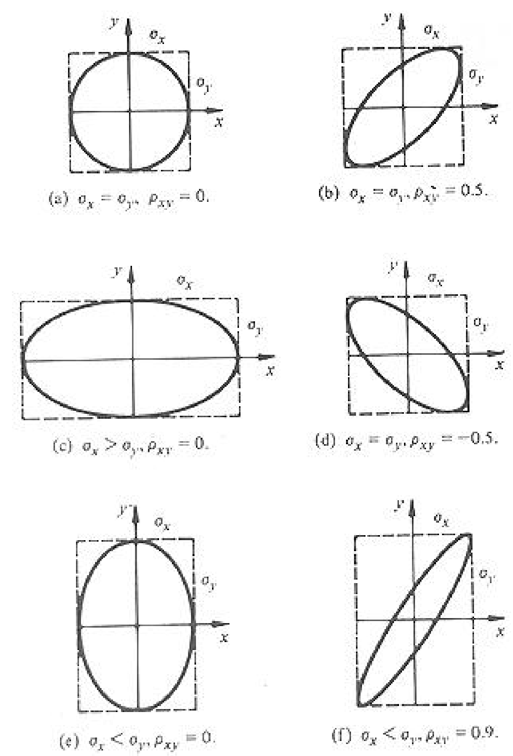

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Figure 2

Note that these figures represent the various effects of a bias as the result of the least squares adjustment of random error. What is most desirable is a result equivalent to ellipse (a) - no bias such that the error figure is equal in all directions - a circle. The further we depart from a circle, the less desirable the result in that a significant bias is displayed**.**

Ellipse (f), then, is the least desirable for a position determination. A shipbuilder is given a quality check tool that on the surface can be viewed as a subjective criterion. The choice of the appropriate math model for the photogrammetric adjustment offers a solid mathematical foundation for the graphical review of "goodness of fit." In surveying, all measurements are made with some degree of error. With an error propagation for the geometric dilution of precision (GDOP) in a 3D analytical photogrammetric adjustment of observations, the result is a realistic estimate of the reliability of measurements. There is less reliance on "experience" and a greater assurance of an objective estimator of the quality of the observations, quality of dimensions and quality of the fabrication accuracy control.

A typical standard error ellipse in the X-Y plane is shown in Figure 3:

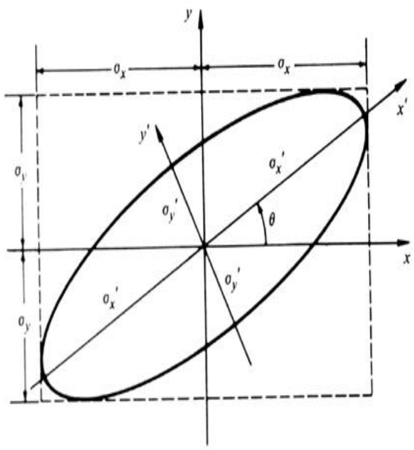


Figure 3

Since c = 1, the imaginary box (broken line) that encloses the ellipse has half-dimensions σ_x and σ_y. In general, the principal axes of the ellipse, x' and y' do not coincide with the coordinate axes X and Y; the major axis of the ellipse, x' makes an angle θ with the X-axis. A positional error is expressed in the x,y coordinate system by random vector [X',Y']. The covariance matrices for random vectors

$$\begin{bmatrix} \mathbf{X} \\ \mathbf{Y} \end{bmatrix}, \begin{bmatrix} \mathbf{X}^1 \\ \mathbf{Y}^1 \end{bmatrix} \qquad (4)$$

are

$$\begin{bmatrix} \boldsymbol{\sigma}_{\mathbf{x}}^2 & \boldsymbol{\sigma}_{\mathbf{xy}} \\ \boldsymbol{\sigma}_{\mathbf{xy}} & \boldsymbol{\sigma}_{\mathbf{y}}^2 \end{bmatrix} \begin{bmatrix} \boldsymbol{\sigma}_{\mathbf{x}}^2 & 0 \\ 0 & \boldsymbol{\sigma}_{\mathbf{y}}^2 \end{bmatrix} \quad (5)$$

respectively. The off-diagonal terms in the covariance matrix for $\begin{bmatrix} \mathbf{X}^1 \\ \mathbf{Y}^1 \end{bmatrix}$ are zero because X' and Y' are uncorrelated (x' and y' are the principal axes of the ellipse).

Applying the general law of propagation of variances and covariances[4] to the vector relationship given previously:

$$\begin{bmatrix} \boldsymbol{\sigma}_{\mathbf{x}}^2 & 0 \\ 0 & \boldsymbol{\sigma}_{\mathbf{y}}^2 \end{bmatrix} = \begin{bmatrix} \cos\boldsymbol{\theta} & \sin\boldsymbol{\theta} \\ -\sin\boldsymbol{\theta} & \cos\boldsymbol{\theta} \end{bmatrix} \begin{bmatrix} \boldsymbol{\sigma}_{\mathbf{x}}^2 & \boldsymbol{\sigma}_{\mathbf{xy}} \\ \boldsymbol{\sigma}_{\mathbf{xy}} & \boldsymbol{\sigma}_{\mathbf{y}}^2 \end{bmatrix} \begin{bmatrix} \cos\boldsymbol{\theta} & -\sin\boldsymbol{\theta} \\ \sin\boldsymbol{\theta} & \cos\boldsymbol{\theta} \end{bmatrix} \qquad (5)$$

Multiplying the matrices and equating corresponding elements,

$$\boldsymbol{\sigma}_{\mathbf{x}}^2 = \boldsymbol{\sigma}_{\mathbf{x}}^2 \cos^2\boldsymbol{\theta} + 2\boldsymbol{\sigma}_{\mathbf{xy}} \sin\boldsymbol{\theta}\cos\boldsymbol{\theta} + \boldsymbol{\sigma}_{\mathbf{y}}^2 \sin^2\boldsymbol{\theta} \quad (6)$$

$$\boldsymbol{\sigma}_{\mathbf{y}}^2 = \boldsymbol{\sigma}_{\mathbf{x}}^2 \sin^2\boldsymbol{\theta} + 2\boldsymbol{\sigma}_{\mathbf{xy}} \sin\boldsymbol{\theta}\cos\boldsymbol{\theta} + \boldsymbol{\sigma}_{\mathbf{y}}^2 \cos^2\boldsymbol{\theta} \quad (7)$$

$$0 = (\boldsymbol{\sigma}_{\mathbf{y}}^2 - \boldsymbol{\sigma}_{\mathbf{x}}^2)\sin\boldsymbol{\theta}\cos\boldsymbol{\theta} + \boldsymbol{\sigma}_{\mathbf{xy}}(\cos^2\boldsymbol{\theta} - \sin^2\boldsymbol{\theta}) \quad (8)$$

Substituting (1/2) sin 2θ for sinθ cosθ, and cos 2θ for ($\cos^2\theta$ - $\sin^2\theta$),

$$\frac{1}{2}(\boldsymbol{\sigma}_{\mathbf{y}}^2 - \boldsymbol{\sigma}_{\mathbf{x}}^2)\sin 2\boldsymbol{\theta} + \boldsymbol{\sigma}_{\mathbf{xy}} \cos 2\boldsymbol{\theta} = 0 \quad (9)$$

from which:

$$\tan 2\boldsymbol{\theta} = \frac{2\boldsymbol{\sigma}_{\mathbf{xy}}}{\boldsymbol{\sigma}_{\mathbf{x}}^2 - \boldsymbol{\sigma}_{\mathbf{y}}^2} \quad (10)$$

The quadrant of 2θ is determined in the usual way from the signs of the numerator $2\theta_{xy}$ and denominator (σ_{x2} - σ_{y2}). Eliminating θ results in the following expressions for the variances of X' and Y':

$$\boldsymbol{\sigma}_{\mathbf{x}}^2 = \frac{\boldsymbol{\sigma}_{\mathbf{x}}^2 + \boldsymbol{\sigma}_{\mathbf{y}}^2}{2} \left[\frac{(\boldsymbol{\sigma}_{\mathbf{x}}^2 - \boldsymbol{\sigma}_{\mathbf{y}}^2)^2}{4} + \boldsymbol{\sigma}_{\mathbf{xy}}^2 \right]^{\frac{1}{2}} \quad (11)$$

$$\boldsymbol{\sigma}_{\mathbf{y}}^2 = \frac{\boldsymbol{\sigma}_{\mathbf{x}}^2 + \boldsymbol{\sigma}_{\mathbf{y}}^2}{2} - \left[\frac{(\boldsymbol{\sigma}_{\mathbf{x}}^2 - \boldsymbol{\sigma}_{\mathbf{y}}^2)^2}{4} + \boldsymbol{\sigma}_{\mathbf{xy}}^2 \right]^{\frac{1}{2}} \quad (12)$$

The standard deviations $\sigma_{x',}$ and $\sigma_{y;}$ are the semi-major axis and semi-minor axis, respectively, of the standard error ellipse. Furthermore, the variances $\sigma 2_{x'}$ and $\sigma 2_{y§}$ are the eigen values of the covariance matrix of the random vector $\begin{bmatrix} \mathbf{X} \\ \mathbf{Y} \end{bmatrix}$.

For the three-dimensional case as provided by a photogrammetric solution, the eigen vectors are provided in the form of a 3X3 matrix of direction cosines for each point and the

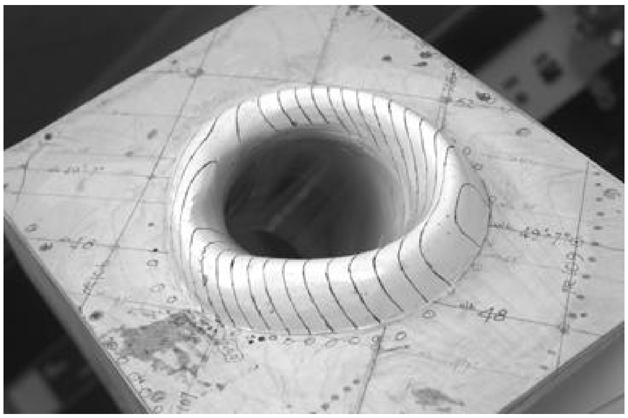
eigen values are provided for each component (σ_x,σ_y, ,σ_z). Graphics software provides 2-D views for the X-Y plane, X-Z plane and the Y-Z plane.

DISCUSSION OF RESULTS

Active participation with a shipyard included:

Shell Bolster Model. Photographs were taken of a scale model (Figure 4) with good geometry and good tonal range. Images were imported to the Desktop Mapping System (DMS®) software. The analysis results appeared good, but initial reaction by shipyard personnel indicated

Figure 4



that discrepancies existed. The actual targets were holes made in the surface of the model by a drafting compass needle. The sizes of the holes varied under magnification, the material around many of the holes were craterous and when the results of the photogrammetric analysis were perused, the units were expressed at full scale. Whatever discrepancies do exist are due to the difficulty in the identification of the photogrammetric targets available. The preparation of the model was intended for mechanical 3D digitization which was used with acceptable results. Although a different method of marking targets might be used in the future for such models, the use of digital photogrammetry is probably inappropriate when mechanical 3D digitizers are accessible.

Double Hull Mid-Body Tanker Section. Informational photographs were taken of a mid-body section under fabrication (Figure 5).

Figure 5

Plans have been made to use the digital camera system in providing dimensional control after an existing ship is cut for later mating to the new mid-body section. As of the end of the period of funded research for this project, the existing ship stern had just been photographed in the dry dock.. Tests were made for target visibility with excellent results. Camera distance was about 27 meters (88 feet) from the mating surface of the stern section, and a 28mm wide-angle lens was used. This particular focal length of lens was chosen because of the physical constraints imposed by the size of the interior of the dry dock. Targets used were office-style labels 32 mm (11/4") round. The beige ship color required a "red glow" target color for contrast. The shipyard made a cherry picker available for the photography session (Figure 6).

The "Red Glow" target stickers were placed (one hour) at the locations where coordinates were desired by the Accuracy Control Section. Photos were taken at nine locations with 100% overlap such that practically every control point and unknown point ("pass point")

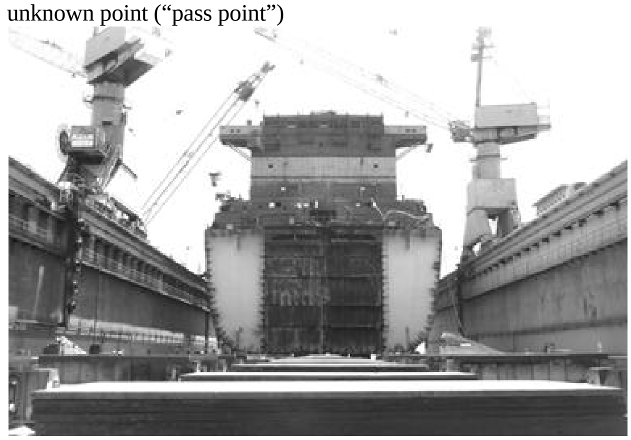


Figure 6

appeared in each of the nine convergent photos. Resulting accuracy's were X= ±4 mm (0.16 inches), Y= ±11 mm (0.433 inches), Z= ±4 mm (0.14 inches) (four hours for analysis) and were deemed acceptable (Appendix A).

Plate Shop / Factory. There is some concern at shipyards with the numerically-controlled flame cutting tables with respect to

differential movement of large steel plates 25mm x 6 m x 18 m (1 inch thick x 20 ft x 60 ft) being cut. Sometimes these steel plates move during cutting, other times they don't. The three-camera system with simultaneous remote control is ideally suited for such an investigation to determine how much movement exists and when & where it occurs. A visit to the plate shop / factory was made and control was established by the Accuracy Control Department. Three cameras were set up, and 3 simultaneous exposures were shot at 10-minute intervals for 2 hours, the period required to cut the subject steel plate (Figure 7).

Figure 7

The results were inconclusive because of camera exposures of the target points. The standard electronic flash units were quite adequate for the distances of less than 61 m (200 feet), but the orientation of the target points (flat retro-reflective tape stickers) were at too shallow an angle to permit sufficient light to return to the camera. (Stickers that were oriented perpendicular to the camera & strobe lights showed up with spectacular light returns at distances exceeding 60 m.) Experiments were initiated to develop retro-reflective targets that would be adequate for such distances and for any angle of incidence. Initial results of target design research can be improved upon by using magnets and ball-bearings painted with various retro-reflective materials. Initially, ball bearings were painted with highway sign reflective paint. The quality of the targets was poor because of the viscous nature of the paint that had glass beads held in suspension. On recommendation from a professional sign painter's supply store, targets were then painted with white primer. In an attempt to replicate the aluminum layer of reflective tape, the targets were then sprayed with a splattered aluminum paint. The targets were then sprayed with aerosol adhesive and coated with spherical glass beads. The resultant targets appear promising.

In addition to the three projects initiated with the shipyard collaboration, two additional projects were completed with potential for shipbuilding applications:

Figure 8

Industrial "As-Built 3D CAD Model." An industrial facility under construction was chosen for a pilot project, and was targeted and surveyed in two hours by two surveyors (Figure 8). The target points were flat retro-reflective circular tape stickers with rectangular tabs attached for ID notes (one hour) (Figure 9). The control consisted of approximately 12 points surveyed to an accuracy of better than 1.6 mm (0.06 inches) in X-Y-Z. The photogrammetric solution included 19 photographs with 2 different focal length lenses. Results were satisfactory and were generally within the requisite accuracy of 6 mm (0.25 inches) in X-Y-Z. The computed coordinates were delivered in the form of a final report. The photogrammetric solution took 16 man-hours. Retro-fitting new equipment into an existing engine room is an application of this easily-implemented technique. The site survey requires only the technician and the camera.

Figure 9

"As-Built" Tugboat Hull Offsets. A Naval Architect needed to determine the "as-built" dimensions of an existing tugboat (M/V J.K. McLean) in order to compute the stability characteristics of the vessel. Desired overall accuracy was $\pm$12 mm (0.5 inches) for all three components (X-Y-Z), and speed of measurement was a major concern in order to *minimize the changes for dry dock rental time* (Figure 10).

Figure 10

The vessel was available at 12:30 p.m., and three men started targeting the bulkhead locations with 10 mm (0.41 inch) diameter reflective tape. The targeting operation took a total of four and a half hours. Four object space control points were surveyed with the aid of a 30 m (100 foot) steel tape and an automatic level. The X-Y-Z control was completed in 15 minutes. A total of 52 photographs were taken with electronic flash in 15 minutes. Total dry dock time was 5 hours. Of the 52 photos taken, 26 were actually used in the photogrammetric analysis. Photogrammetric analysis time totalled 48 hours because of two blunders - one blunder in the reduction of the object space control points of approximately 0.33 m (1 foot), one blunder because of duplicate point identifications assigned during the measurement phase. Thirty seven hours were because of human error; actual productive work would have taken about 12 hours if there were no blunders. Final accuracy was $\pm$8 mm (0.33 inches) in X (lengthwise along the keel), $\pm$9 mm (0.35 inches) in Y (width offsets perpendicular to the keel) and $\pm$5 mm (0.20 inches) in Z (vertical). The blunders were made in the office and were corrected in the office.

CONCLUSIONS

Digital image photogrammetry is a system that is reliable and easily implemented with “off-the-shelf” equipment and inexpensive topographic mapping software. Higher accuracy’s can be obtained by modeling more sources of systematic error such as lens distortion. Greater functionality can be obtained from the system by customizing the topographic mapping software to a more specific shipbuilding context; specifically with respect to units of measurement and reference conventions. A phototriangulation software package that computes the error propagation of the Geometric Dilution of Precision is a necessity for reliable production Quality Checks.

RECOMMENDATIONS

The results demonstrated that existing inexpensive topographic mapping software with GDOP error propagation analysis can be used with high-resolution CCD cameras for shipbuilding and industrial 3D “as-built” applications. It is recommended that work continue for target design, software to easily connect applications, and to develop a training package to facilitate technology transfer of inexpensive terrestrial photogrammetry software & techniques to the U.S. Shipbuilding Industry.

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The New Attack Submarine: A 21st Century Design

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ABSTRACT

Nuclear submarine design for the 21st century embraces world class processes, technology, and tools. The walls which once divided engineering disciplines have been replaced by multi-functional teams. Designer and shipbuilder independence of the past is being replaced by interdependence; and the arms-length relationship with suppliers and the Navy is being replaced by cooperative, interactive teaming arrangements. The goal of everyone involved in the design of the New Attack Submarine (NSSN) is to work together to provide the most cost-effective and capable product.

In 1989, Electric Boat Corporation initiated a comprehensive review of the submarine design and construction process with the goal of reducing nuclear submarine acquisition and life cycle cost. The process was mapped for each technical discipline (electrical, structural, piping, etc.), step-by-step, and optimized around a fundamental core process to eliminate inefficient work practices. Concurrent with this internal review was an external evaluation of design and construction methods being utilized throughout a broad spectrum of U.S. and international industries. Designers and manufacturers in the aircraft, automobile, power plant equipment, reactor plant equipment, and shipbuilding industries were visited to observe their design and manufacturing processes. In addition, numerous articles and papers written on concurrent engineering were reviewed, paying particular attention to lessons learned.

These comprehensive reviews, conducted over two years, identified the best features of current industrial practice. These "best practices" were adapted and incorporated into the structure of the NSSN design process to ensure maximum producibility of the ship design. As a result, the NSSN design is being developed utilizing the basic concurrent engineering concept optimized to nuclear submarine product development. Designers, construction personnel from each major trade, and key support personnel work together on teams to produce design drawings for ship construction that consider material availability and ease of construction (producibility).

Integral to the process review was an evaluation of computer tools and software available to support the next generation of submarine design and construction. CATIA, the IBM/Dassault Digital Design System, and CATIA Data Manager (CDM), were selected as the base set of programs. These integrated tools have enabled both the production of the highest quality construction drawings, and an efficient change process, which reduces the average design change period from many days to a fraction of a day. Four key elements have been hallmarks of recent successful military and commercial programs:

- *A clearly defined program concept,*
- *Concurrent engineering,*
- *Formation and full utilization of a complete computer design database, and*
- *An organizational structure that facilitates concurrent engineering.*

PROGRAM CONCEPT DEFINITION

Concept planning for the country's next generation attack submarine began with one objective: Produce a less expensive, very capable alternative to the SEAWOLF Class submarine. The design objective of the NSSN Program is to produce a multi-mission submarine with SEAWOLF acoustic performance, the capability for efficient mission equipment modification, with acquisition cost equal to, or lower than, the cost of additional SSN 688 I's, and low life cycle cost.

As part of the shipyard and Navy concept formulation (CONFORM) efforts, numerous ship design alternatives involving significant parameter variations were studied in detail with appropriate tradeoffs considered before deciding on the baseline NSSN design characteristics. These evaluations were performed by an integrated team of designers, engineers, shipbuilders, planners, quality control experts, and cost estimators, who worked closely with the Navy in the evaluation of each alternative.

A structured evaluation process for platform integration, was used to establish design parameters. This evaluation and review of ship design alternatives is an integral part of the early design phase of every submarine program. However, the significant difference for the NSSN Program is the use of computerized solid modeling tools. Many variations of basic designs were studied in a shorter period with greater accuracy than on past submarine programs. By establishing this process, potential performance improvements have been and are continually being evaluated based on cost and overall platform capability.

The NSSN modular design will enable it to respond to changing missions, threats, systems, and resources. New technologies and components can be inserted during construction or backfit to enhance operational capabilities and reduce life cycle costs.

Concurrent Engineering

The NSSN Program is a closely integrated effort. The shipyard and the Navy worked together in a common office for several months to develop the NSSN Ship Specifications. Close communication between all parties has been achieved via concurrent engineering through the “Design Build” team process. Teams practice concurrent engineering by grouping designers, engineers, ship-builders, material personnel, planners, life-cycle support and environmental impact personnel, quality and cost personnel, equipment suppliers, representatives of Knolls Atomic Power Laboratory (KAPL), Bettis Atomic Power Laboratory, the Navy Supervisor of Shipbuilding (SUPSHIP), Groton, and other Navy representatives in an active design process. By integrating functional specialties ondesign build teams, the shipbuilder is able to tailor the design to suit the planned method of construction. At issue, design drawings suit the shipbuilder’s construction plan. This designer/shipbuilder interaction results in the most producible ship design.

All activities play a role in the development of design products. The results are:

- High quality construction deliverables and
- Fewer changes are required/due to design errors.

Problems raised by each agency are resolved during the development process rather than during construction. An integrated design involves all stakeholders up front, where it counts. Integration of Government input not only reduces the number of formal Government approvals, but also results in a reduction of the overall approval administration documents.

The NSSN concurrent engineering process is a leadership approach that empowers design build teams to develop the design products.

The teams are given authority based on program objectives to ensure that their specific products are developed in a timely, efficient, producible and high quality manner.

The NSSN concurrent engineering process has been developed in concert with design and construction labor unions. It is a working partnership in which union members are active members of design build teams. Union participation as partners in the entire concurrent engineering effort has fostered a mutual respect for the talents that are contributed. Union leadership and Corporation leadership are committed to working together as an efficient business team for the mutual benefit of the employees, the shipyard, and the Navy.

Computerized Design Database

The NSSN Program utilizes a substantial computerized design database which enables full integration of all activities. Each functional discipline has real-time access to the database so that their design efforts can be performed concurrently. Traditionally, this has been a series process with paper being transferred back and forth resulting in a step function rather than a smooth continuous design effort. In addition, without a centrally controlled database, design development occasionally proceeded with different arrangement baselines, which led to rework. With the design data available on a digital network, production can be facilitated without the need for manual or graphical hard copy transfer of data. The same data used for the design can be used to drive numerically controlled manufacturing processes from the design database without physical drawings. The database can directly control cutting torches and pipe bending machines.

The primary interface between the design build teams and the electronic design database takes place in Electronic Visualization System (EVS) rooms. There are five EVS rooms at the shipyard, and additional rooms at KAPL, Navy offices, and at key equipment suppliers' facilities. These rooms provide full multimedia presenta-tion of the design and permit interaction with it.

Close communication via video conferencing provides KAPL and the Navy an in-depth knowledge of the design and its

progress, as well as fully utilizing their knowledge and contribution to achieve the best design. By using common electronic data, the need for physical models and mockups is substantially reduced. Collaboration takes place through digital data exchange and through continual design review of product model data using the electronic mockup. These data links enable the design groups to participate in model tours/reviews and conferences, thereby establishing a higher level of participation, contribution, and timely concurrence, as the design progresses.

The Design Build team members, including equipment suppliers and customer personnel, can see the details of the design at any stage of development and can interactively create, view, and modify design information. Objects can be instantaneously manipulated. Immediate feedback enables team members to identify and correct problems. Each week, electronic video conferences are conducted between the involved design parties to review the detailed design status, addressing problems that require discussion and joint resolution.

The computer database is a full service resource which contains all the information needed to support current activities such as procurement, construction drawings, automated production, logistics, electronic mockups, and downstream activities such as future repair, replacement or modification needs. As such, this database becomes both a tool for initial development of the design, for ship construction, and for its through-life support.

Organizational Structure

Successful concurrent engineering requires that an organization be structured to accommodate co-located and/or video-linked design build teams by including all appropriate functional areas. The organization structure must also convey to the design build teams the authority and responsibility for their products.

An Electric Boat Program Manager has been appointed, who has overall ship design and construction responsibility for the Program. This Program organiza-tion structure ensures a concentrated focus for the entire design and construction effort, as well as establishing a single point of contact for all Program interfaces from the beginning of design through life cycle support of the ships.

The organizational structure instituted for multi-function, co-located design build teams, eliminates independent product development in favor of truly integrated product environment development. It includes about 75 System Integration Teams, who design complete systems and structures throughout the ship. There are 15 Major Area Teams that are responsible for design of the major construction modules of the overall ship assembly. These teams provide the continuity of knowledge from design through construction and delivery.

Each design build team is held responsible for its products. This assignment of responsibility takes advantage of multi-discipline teaming, and fully utilizes discipline-specific expertise in the shipyard, in the suppliers' organizations, and in the Navy. Organizationally, these knowledgeable resources are designing the ship for efficient construction.

RESULTS

Four years into the new design and engineering process, the New Attack Submarine is taking shape at a brisk pace. What were once digital concepts on a screen are quickly becoming a validated design and detail construction deliverables. The defined program concept, concurrent engineering, use of a totally computerized design database, and a coordinated organizational structure have facilitated initiatives such as the following which have been implemented to improve design and construction performance, improve military capability and reliability, while reducing acquisition and life cycle cost. Results of this process include the following.

- A fully integrated master schedule has been developed which defines and integrates all design and construction activities from start of design through ship delivery. This schedule provides each activity the ability to review and plan the work tasks 2 - 3 years in advance.
- Shipboard systems have been simplified with a reduction in shipboard equipment.
- A fully comprehensive cost reduction program has been instituted covering design and construction processes for initial acquisition and life cycle support. Approximately 4,000 "good ideas" have been identified and evaluated by the shipyard, equipment suppliers, and customer organizations.
- Parts standardization has drastically reduced the number of different parts used. The NSSN design uses just 1/5 to 1/3 the number of unique parts used in previous designs.
- Early involvement of equipment suppliers in equipment specification development allows use of existing products and processes rather than forcing unique design and test requirements on suppliers.
- Commercial specifications rather than military specifications have been invoked where possible. For example, 90% of the fasteners used on NSSN are commercial specification.
- Environmental considerations are addressed for procurement, construction, life cycle support activities and disposal costs.

The design knowledge gained by the design build teams, the tailoring of the design for producibility, the refinement of the design developed through computer modeling, the standardization of material parts, and the initiatives taken to ensure timely material availability, will all contribute to an efficient construction process never before experienced on a U.S. nuclear submarine lead ship of a class. Integration of design and construction personnel in the design development process will greatly facilitate cost effective construction support because both functions will have participated in development of the design drawings and construction plan.

CONCLUSION

In this era of changing defense requirements, emphasis is

shifting away from weapons systems designed to counter specific targets, and is moving more toward versatile systems that are effective against a broad range of threats and readily adaptable to evolving missions. Such is the case with the New Attack Submarine. As the first U.S. nuclear submarine designed to face the certain, but indistinct challenges of the next century, it must be adaptable to multiple missions and unforeseen scenarios worldwide. Its military capabilities must cover the warfare spectrum from covert surveillance and deployment of Special Forces to sudden attacks against land targets with precision missiles. And, the price to acquire and maintain that submarine must be one that the nation can afford.

The New Attack Submarine design is proceeding utilizing the four key elements found successful in other major production programs:

- A clear definition of the program concept,
- A world class concurrent engineering process,
- State-of-the-art tools, and
- An organization tailored for the New Attack
- Submarine design and construction evolution.

Working together, the Navy and Electric Boat are designing a submarine that will provide the required military capabilities while meeting cost objectives.

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CAD/CAM/CIM Requirements For A World Class Commercial Shipyard

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ABSTRACT

With their ongoing reentry into the international shipbuilding market, U.S. shipyards are focusing on the strengths and potential of computer-aided design/computer-aided manufacturing/computer-integrated manufacturing, or CAD/CAM/CIM. World-class commercial shipyards and software suppliers in Europe and Japan have advanced the state of the art of CAD/CAM/CIM and offer much for U.S. yards to learn. Indeed, they have proven generous in sharing their knowledge with the U.S., as evidenced during the conduct of the recent National Shipbuilding Research Program "Evaluate the Shipbuilding CAD/CAM Systems" Project.

The primary goal of Phase I of the Project was to identify key features of CAD/CAM/CIM implementations at world-class shipyards that most significantly contribute to the success of those shipyards in commercial shipbuilding and deliver this information to U.S. shipyards. That goal has been accomplished and the results presented at a CAD/CAM/CIM workshop at the 1996 Ship Production Symposium. This paper reports on Phase II of the CAD/CAM/CIM project, which built upon the knowledge gained in Phase I. In Phase II, the Project Team developed a set of 70 technical requirements for a world-class ship design and production CAD/CAM/CIM system that is future-oriented. In addition, the Team described links between the technical side of shipbuilding and the business side, illustrating the business value of the technical requirements in particular and advanced CAD/CAM/CIM in general.

It is hoped that the technical requirements and business links will provide U.S. yards with guide posts which will help those yards not only catch up with, but leapfrog, world-class technology and establish a competitive presence in the international shipbuilding market.

Key words: CAD, CAM, CIM, Business, Computer, Shipyard, Shipbuilding, Design, Requirement

NOMENCLATURE

CAD Computer-Aided Design
CAM Computer-Aided Manufacturing
CIM Computer-Integrated Manufacturing

INTRODUCTION

This paper is based work performed during the conduct of Phase II of National Shipbuilding Research Program (NSRP) Project 4-94-1 to evaluate world-class shipbuilders' CAD/CAM/CIM system implementations. Five U.S. shipyards (Avondale Industries, Bath Iron Works, McDermott Shipbuilding, Newport News Shipbuilding and National Steel and Shipbuilding) participated in this study along with personnel from University of Michigan, Proteus Engineering and Cybo Robots. All of the individuals were key contributors to the practical application of computer aided manufacturing technology in the U.S. shipbuilding industry.

The CAD/CAM/CIM Project comprised three phases, as follows:

- Phase I - Evaluate Existing Systems - Visit world-class shipyards in Europe and Japan and learn about state of-the-art shipbuilding CAD/CAM/ CIM implementation approaches.
- Phase II - Requirements - Build upon the knowledge gained in Phase I to develop a set of requirements for a competitive, future-oriented shipbuilding design and production CAD/CAM/CIM system.
- Phase III - Workshops - Prepare for and conduct workshops that show how CAD/CAM/CIM technology requirements relate to shipyard management from a business perspective.

The Phase I results were presented at a two-day workshop and a paper [1] at the 1996 Ship Production Symposium and in a formal report [2]. In-depth descriptions were provided of the visits to shipyards, allied industries and software developers. It was noted that, while aggressive business practices were keys to ensuring the success of high technology shipyards, those shipyards used CAD/CAM/CIM to gain competitive advantages over low technology yards through approaches such as:

- Development of more complete, consistent, production-oriented design packages;
- Earlier project schedule and planning simulations; and,
- Improved ability to coordinate design, procurement and production within the entire enterprise (shipyard, vendors, customers and regulatory bodies).

Without exception, the shipyards and software vendors that the Team visited continue to strive for improvement. Example future plans included [2]:

- More complete product modeling, including integration with shipyard process modeling, especially in the robots areas;
- Increased automation in the design process, using “rules” to facilitate the CAD process and concurrently incorporate production process considerations;
- Increase automation in production, again, with an emphasis on robots;
- Integration with economic decision making;
- Improve cost and performance computing hardware;
- Improve product model databases and develop interfaces that are more industry standard;
- Develop Windows NT versions of product model software;
- Develop knowledge-based software;
- Improve visualization capabilities, including capability for walk-throughs;
- Enhance computational and design capabilities (e.g., hull form development and computational fluid dynamics);
- Provide integration of product model systems with third party programs (e.g., material management);
- Develop improved tools for quick development of designs for tendering; and,
- Develop enterprise-wide automation and communication.

The following sections describe key aspects of the Phase II effort [3], including a description of the requirement development process; a presentation of the CAD/CAM/CIM requirements developed by the Project Team; a description of a requirement selection methodology; and conclusions and recommendations resulting from lessons learned during the conduct of the Project.

THE REQUIREMENT DEVELOPMENT PROCESS

Requirements development is one stage in the software life cycle process. This process may be summarized by the following steps:

1. Determine user needs
2. Develop software requirements
3. Develop software specifications
4. Conduct programming
5. Test and debug
6. Implement, train users
7. Maintain
8. Decommission.

The steps most relevant to this paper are (1) and (2) which parallel Phases I and II of the NSRP Project.

Where Requirements Fit Within the Software Development Process

In this creative process, requirement descriptions usually tend to be "generally poor," not because of any fault of the software designers or of the process, but rather because all requirements are not known until the software is developed and users try it out [4]. Because the rest of the design process is based on the requirements, every effort should be made to make the requirement descriptions as complete, accurate and precise as possible; this was the goal of the Project Team.

Requirements have several characteristics. They are:

- Derived based on an understanding of user needs,
- Written statements,
- Tell what the software must do, and they
- Tell how the software is structured.

Requirements do <u>not</u> tell how the software is programmed.

There is a difference between the goals of the NSRP Project and a ship production software development project. The CAD/CAM/CIM Project did not result in actual software. Rather, ship production needs have been identified and CAD/CAM/CIM requirements have been developed.

The requirements should be viewed collectively as the needs of future-oriented, commercial shipbuilding CAD/CAM/CIM software. The requirements are not to be thought of as comprising modules of such software, but rather as features which are to be found within the software. The requirements do not tell how to design the software, they simply state needs the software must fulfill. Thus, various solutions may exist, each of which may meet the requirements, but in different ways. There is no single "right" solution.

Testing

Testing is the approach that software developers use to detect and correct errors. It has been stated that "more than half the errors are usually introduced in the requirements phase"[7]. To prevent migration of errors onward to the specifications phase and beyond, testing should be carried out as part of the development of requirements. In fact, testing and error correction should be carried out at each phase of software development. For example, the following checklist, adapted from [6] and [7], may be used to test requirements.

- <u>Complete</u> - All items needed to specify the solution to the problem have been included.
- <u>Correct</u> - Each item is free from error.
- <u>Precise, unambiguous, and clear</u> - Each item is exact and not vague; there is a single interpretation; the meaning of each item is understood; the description is easy to read.
- <u>Consistent</u> - No item conflicts with another item.
- <u>Relevant</u> - Each item is pertinent to the problem and its solution.

- Testable - During program development and acceptance testing, it will be possible to determine whether the item has been satisfied.
- Traceable - Each item can be traced to its origin in the problem environment.
- Feasible - Each item can be implemented with the available techniques, tools, resources, and personnel, and within the specified cost and schedule constraints.
- Free of unwarranted design detail - The requirements are statements of what must be satisfied by the problem solution, and they are not obscured by proposed solutions to the problem.
- Manageable - The requirements are expressed in such a way that each item can be changed without excessive impact on other items.

CAD/CAM/CIM REQUIREMENTS

The CAD/CAM/CIM requirements are those elements that were identified by the Project Team as necessary for a competitive, future-oriented shipbuilding design and production CAD/CAM/CIM system.

Requirements Listing

A requirements listing was developed and refined as the project progressed. This listing formed a basis for questions asked and information gathered during shipyard, vendor and allied industry visits by the Team. The requirements were organized to be consistent with U.S. shipyard typical practices. All requirements were first grouped into the general areas of Design, Production, Operations Management and Umbrella (the Umbrella area covered requirements generally common to one or more of the other areas). The requirements were further subdivided into detail areas as follows.

Design
- Conceptual/Preliminary Design
- Functional Design
- Detailed Design

Production
- Fabrication Processes
- Joining and Assembly Processes
- Material Control
- Testing and Inspection

Operations Management
- High-Level Resource Planning and Scheduling
- Production Engineering
- Purchasing/Procurement
- Shop Floor Resource Planning and Scheduling

Umbrella
- Umbrella

How Requirements are Described

Requirements are described on 'requirement sheets.' One sheet containing the information described below is provided for each requirement.

- Requirement - Descriptive title of the individual requirement.
- State of development - Indication of how far the requirement has advanced toward actual practice: conceptual stage, initial development, prototype testing, proprietary versions and available on the market. A requirement may be at several stages of development. For example, a requirement may exist in software that is proprietary in one shipyard, yet also be available on the market in other software. The most advanced of the choices is provided on the requirement sheet.
- Description - Definition of the requirement and explanation of its role in the context of a CAD/CAM/CIM system.
- Potential business benefits - Description of how the requirement can help a shipyard from the business perspective, for example, in the areas of innovation, addressing a customer's needs or through optimization.
- General area - Denotes which of four overall categories apply to a given requirement.
- Detail area - Denotes which of 13 particular categories apply to a given requirement.

The full list of requirements is presented in the Appendix, grouped in this two-tier manner.

REQUIREMENT SELECTION METHODOLOGY

General

Not all shipyards will want, need or be able to afford all of the requirements listed in the previous section. Thus, a selection methodology is needed to choose those requirements that will best serve the needs of each particular shipyard. As a first step in this methodology, shipyard upper management should define their strategic plan, considering elements such as the following:

- Market leadership goals,
- Strategic direction of the shipyard,
- Planned response to market needs,
- Costs of implementing CAD/CAM/CIM,
- Design and production processes within the shipyard,
- Relationships with suppliers and vendors, and
- Relationships with customers.

Whatever the detail of the strategic plan, of paramount importance is the involvement and buy-in of upper management with regard to CAD/CAM/CIM selection and implementation. Involvement commonly includes educating upper management in the general capabilities of CAD/CAM/CIM. Without the involvement of upper management, there may be no connection between the CAD/CAM/CIM system that is selected and the business results envisioned in the shipyard's strategic plan [8].

CAD/CAM/CIM selection is a melding of business and technology in the shipyard. In a larger sense, the selection methodology may be viewed as a way to align technology with business results, which is a major theme of this paper. Two key steps for achieving this alignment are to [8]:

- Plan for innovation, customization, and optimization, and
- Use the theory of constraints to identify priorities.

The sections below describe these two steps; show how they are used as part of a selection methodology; and provide examples from industry that illustrate the methodology.

Innovation, Customerization and Optimization

CAD/CAM/CIM technology requirements may be aligned to business objectives by using the following equation [8]:

$$MS_1 \times MS_2 \times MS_3 = \text{Profit} \qquad (1)$$

Where,

MS_1 = Market Size,
MS_2 = Market Share, and
MS_3 = Margin on Sales.

For example, if a shipyard has a 10% share (MS_2 = 10%) in a $100 Million market ($MS_1$ = $100 Million), and its margin on sales are 20% (MS_3 = 20%), then,

$100 Million x 0.10 x 0.20 = $2 Million Profit.

The thinking in this approach is that everything a company does should improve at least one of these three areas. Thus, these areas can be used to track trends and evaluate alternative business actions. Looking at each area in detail provides further insight as to their use:

Market Size (MS_1) - Create or participate in attractive markets through new product innovation. **Innovation** drives market size.
Market Share (MS_2) - Win market share against competitors by providing products and services customers prefer. **Customerization** drives market share.
Margin on Sales (MS_3) - Earn healthy margins by some combination of earning a premium price and/or being the lower-cost provider. **Optimization** drives margin on sales.

Figure 1 expands upon these areas. Note that the three areas are not mutually exclusive; a shipyard may simultaneously participate in two or even all three areas, especially if the yard is working several projects, some at the conceptual and marketing stage, others at more advances stages of production.

Use of the Theory of Constraints to Identify Priorities

The Theory of Constraints is a way to focus on where to improve a process. For example, a shipyard may want to improve throughput in a plate nesting and cutting operation. At first, the best approach may seem to be replacing an existing manual cutting operation with robotics. Closer study may show that robotic cutting would reduce the number of personnel in the operation, but not increase throughput, because of downtime while waiting to receive cutting data: robots or people could work only a fraction of the time, and must wait the rest. Thus, throughput would remain as before. In this case, the constraint is the lofting operation, which is slowing down the overall throughput. If the lofting time is decreased (for instance, through CAD/CAM automation), then the constraint is removed.

Knowing the constraints in the shipbuilding process will help a shipyard focus on how CAD/CAM/CIM technology can improve that process. The principles of the Theory of Constraints may be summarized as follows [8]:

- The throughput of an entire system is held back by constraints. Constraints may be both physical (e.g., limited throughput of computer systems) and non-physical (e.g., bureaucratic procedures or competition between departments); thus, a thorough knowledge of the process being evaluated is mandatory.
- Most systems have relatively few real constraints. Improvements at just these constraints will dramatically improve throughput. However,

  "gains" in areas where there are no constraints has zero value.
- Traditional measures of productivity fail to recognize the importance of constraints. For example, a 10% productivity improvement on a $10/hour clerical job might really be worth $1000/hour to the company, while a 30% improvement on a higher profile $100/hour job may prove worthless.
- Constraints provide a focal point for managing the entire system.
- Constrained processes should run as close to 100% efficiency as possible. Never starve them for necessary inputs. Keep non-productive times (e.g., set-ups) to a minimum.
- In manufacturing operations, inventories usually pile up in front of bottleneck operations.

The ultimate constraints, which may sound all too familiar to those in the shipbuilding industry, are:

- Markets with slow growth (for U.S. shipbuilders, the traditional market is actually shrinking, through cutbacks in Navy orders);
- Inability to break through the competition (the Koreans increase their capacity, the Japanese increase their efficiency and the Europeans remain fiercely competitive); and
- Difficulty in optimizing processes and products to achieve higher margins (changing processes, software and production lines is daunting).

The following questions define whether something really is a constraint.

- Back-up - Is this operation a back-up for work?
- Impact on product delivery - If this process is backed up for a day, is delivery delayed for a day?
- Impact on $(MS)^3$ - If this operation were performed better, would that improvement be reflected in improved market size, market share or margins?

BUSINESS AND MARKET GOALS

MARKET SIZE	MARKET SHARE	MARGIN ON SALES
- today? - trend for future?	- today? - trend for future?	- today? - trend for future?
⇓	⇓	⇓

CUSTOMER INTEREST	CUSTOMER CHOICE	CUSTOMER LOYALTY
drives market size	drives market share	internal costs drive margin on sale
⇓	⇓	⇓

PROCESS PERSPECTIVE

INNOVATION	CUSTOMERIZATION	OPTIMIZATION
Innovation creates customer interest and increases the market for new products. The goal is to be not just first, but right to market. For new features, aim to delight customers.	Customerization satisfies customer needs and maintains or grows market share. The process goes beyond concurrent engineering to sharing knowledge between all functions, customers, and suppliers.	Optimization increases perceived value and lowers costs, leaving higher margins for the company. Creating and maintaining customer loyalty decreases the cost of sales and increases profits. Lower costs, with on loss of perceived value, contribute directly to the bottom line.
⇓	⇓	⇓

TECHNOLOGY ALIGNMENT

CAD/CAM/CIM TO SUPPORT INNOVATION	CAD/CAM/CIM TO SUPPORT CUSTOMERIZATION	CAD/CAM/CIM TO SUPPORT OPTIMIZATION
could include 2D and 3D brainstorming, what-if analysis, visualization, simulation, getting physical fast, rapid tooling. The tool must be easy for innovators, who will not be full-time users.	should link diverse and broadly dispersed knowledge workers. In addition to a wide variety of applications, networking, data sharing, and support are important issues.	will often include computing intensive applications. May be able to justify "best in breed" solutions that integrate with the primary tools for design review. (Without some level of integration, optimization in on area may adversely affect another.)

Figure 1
Framework for Aligning Business, Process and Technology
(Based on Figure III-7 of [8])

Selection Methodology

The selection methodology is a way for a shipyard to choose its CAD/CAM/CIM system. As mentioned above, this process must involve upper management and must be based on achieving business results. The steps of the selection methodology are as follows (see Figure 2).

1. Conduct business assessment - The real objective is "business results," so begin by defining the shipyard's goals in the areas of market size, market share and margins. This is commonly a task of top management. The goals are stated in a shipyard's business strategy.
2. Define new processes - New processes (which may be variations of existing processes) will be necessary as a result of the new direction defined in Step 1; old processes, even with new tools, will yield old results. The processes may run in parallel, and will comprise one or more of the *innovation, customerization and optimization* areas. It is important to define the process before choosing requirements or technologies.
3. Identify priorities - Use the Theory of Constraints to identify problem areas in processes. This is a critical link between *productivity improvements* and *business benefits*.
4. Select requirements - Select appropriate requirements that will address the priorities of Step 3. Many of the requirements of this paper should apply to U.S. shipyards' priorities (modifications or additions will be appropriate in certain cases). While all the requirements may look attractive, care should be taken to select only those applicable to the identified priorities.
5. Select technologies - Technologies (e.g., a new CAD system) should be selected to meet the requirements of Step 4.

This selection methodology is business driven and not technology driven. Shipyards may be tempted to purchase new technologies (such as a product model CAD/CAM system) without thinking through the implications at the business level. Will the new CAD/CAM system reduce or remove a constraint in the shipyard? Sometimes that question is assumed to be "yes" but not actually investigated.

In conjunction with this selection methodology, shipyards should ensure that the expectations of affected people are set. Changes in processes mean that changes in behavior and organization are often necessary. For example, CAD/CAM/CIM tools may eliminate the need for a lofting department. Loftsmen may find themselves part of a design team or they may be shifted

to production. In either new role, the loftsmen's prior experience in ship hull forms would be applied to a part of a new process. The loftsmen would be expected to learn and contribute to the new process and understand that it is different from the process they had participated in prior to the adaptation of CAD/CAM/CIM. Generally, everyone involved in CAD/CAM/CIM changes must be aware of the expectations placed upon them, from top management to shop personnel.

Examples from Industry

To illustrate the selection methodology, several examples have been chosen from industry. These examples were observed by members of the Project Team. The requirements were chosen from the list in the Appendix. One example illustrates each of the three business areas:

1. Conduct Business Assessment

⇓

2. Define New Processes

⇓

3. Identify Priorities

⇓

4. Select Requirements

⇓

5. Select Technologies

Figure 2
Selection Methodology

Market Size (MS_1) - Innovation: Odense Steel Shipyard
Market Share (MS_2) - Customerization: Japanese CIM Project
Margin on Sales (MS_3) - Optimization: Black and Veatch

Each is summarized in Table 1 and discussed in the following paragraphs.

Innovation: Odense Steel Shipyard - Odense Steel Shipyard is located in Odense, Denmark. The shipyard makes use of a number of CAD/CAM/CIM systems, integrated to work together, including HICADEC, NAPA, PROMOS, NISA and DPS. The yard carries out the design as well as the production of large, ocean-going ships, typically VLCCs and containerships.

Odense has developed a balance between manual and automated systems in areas such as material handling, marking, cutting, positioning and welding. A key goal of the yard is controlling the shipbuilding process. Toward this end, there is a high degree of automation in design and planning, including production simulation, all readily addressed by their CAD/CAM/CIM system. On the other hand, there is manual intervention in much of material handling, marking and welding. Automation is evident in repetitive process, such as fabricating built-up profiles and (using robots) certain well-defined welding tasks. Trends at the yard include increasing the proportion of automation and further refining the CAD/CAM/CIM system, both as means to help increase production efficiency, as measured by minimized build time. Through its present strategy, efficiency is increased both directly (e.g., by decreased welding times through robotic welding) and indirectly (e.g., by driving increased accuracy and quality to meet robotic welding tolerance requirements).

As shown in Table I, Odense's business assessment targeted the marketing segments of double hull VLCCs and large containerships. A recent Odense initiative was aimed at innovation (increasing market size through innovation -- MS_1). The idea was to construct containerships of 6000+ TEUs, larger than any previous size, thus permitting owners to reduce the number of ships in their fleets as well as realizing other business-related advantages.

As part of the successful design, Odense maximized the number of containers for a given hull volume through a new type of container guide. The new guide increased the number of containers that the ship could carry, but introduced a production constraint: vendors do not produce structural shapes of sufficient accuracy. The yard decided to cut and form the container guide shapes in house, within the context of requirement 19, "Processes to Cut/Form Structural Plates and Shapes." The yard had to review their existing capabilities for generating NC data to loft, nest, bevel, cut and schedule work into their production area.

In the resulting process, the yard began with steel plate, carefully specified to be within acceptable thickness tolerances. The plate was cut, edge treated and fabricated into container guides. The operation, from generating NC data to fabrication, has proved successful and the first ship of this type has been launched.

Customerization: Japanese CIM Project - The Japanese CIM Project was conducted in the late 1980s and early 1990s [5]. The project was a cooperative effort among Japanese shipyards and was aimed at strengthening the management structure in the participating yards through emerging computer-based technology. The effort was aimed at countering the shipbuilding competition from Korea and maintaining Japan's share of the market.

This project comprised several initiatives, including development of a conceptual version of a 'frame model.' The frame model is a shipbuilding industry computer integrated manufacturing (SICIM) methodology. It encompasses design and production and was designed to be flexible enough to be expanded in scope. The methodology was aimed at changing the ship design and production planning process.

The constraint addressed by the project was a lack of integrated design and production capability. If this constraint could be reduced, the Japanese projected that their competitive position with the Koreans would improve to such an extent that the Japanese market share would benefit. The effort was carried out by teams from seven Japanese shipyards: Mitsui Shipbuilding, Sumitomo Heavy Machine Industry, NKK, Kawasaki Heavy Industry, Ishikawa-Jima Takuma Heavy Industry, Hitachi Shipbuilding and Mitsubishi Heavy Industry. Each team addressed a separate task. For example, the Mitsubishi Heavy Industry Team's goal was two-fold:

- Confirm whether it is possible to enter design information about curved parts in an expanded product model, and,
- Find out if simulation based design facilitates generation of a

preliminary body of design information and is useful for scheduling.

As the above description of scope makes evident, the Japanese CIM Project encompassed an 'enterprise product model,' as defined in Requirement 64 (a central database that encompasses not only the technical aspects of design, but planning and scheduling aspects as well). The Japanese were well equipped to take on such a task, given their history of successful CAD/CAM programs, such as HICADEC, used at Hitachi Shipbuilding in Japan and Odense in Denmark. The project results comprise conceptual developments and pilot studies in selected areas. The efforts of the teams were reported individually, thus becoming a source of data for each yard to continue further development on its own.

Optimization: Black and Veatch - Black and Veatch is an engineering and construction firm specializing in the fields of energy, environment, process and buildings. Headquartered in Kansas City, Missouri, where it was founded in 1915, the firm provides comprehensive planning, engineering design, and construction services to utilities, commerce, industry and government agencies [9]. Since the late 1970s, the company's president and management have backed the expenditure of more that $50 million on CAD/CAM/CIM technology development. The result of the effort was the development of Powrtrak, a proprietary software program used to design power plants for electric utilities. Among other features, Powrtrak allows changes made by any user to be stored systemwide [10]. This is a 'datacentric' concept, and

SELECTION METHODOLOGY	ODENSE STEEL SHIPYARD	JAPANESE CIM PROJECT	BLACK AND VEATCH
1. Conduct Business Assessment	Need for a new product in the containership field	Need to increase market share, especially with regard to Korea	Need to increase margin in the power plant industry
⇓	⇓	⇓	⇓
2. Define New Processes	Process to produce accurate container guides	Process to efficiently carry out ship design and production planning	Process to reduce the costs associated with risk
⇓	⇓	⇓	⇓
3. Identify Priorities	Constraint: vendor-produced structural shapes decreased yard's capability for accuracy or speed of production of guides	Constraint: lack of integrated design/production capability	Constraint: insufficient availability of design and production information to all project participants
⇓	⇓	⇓	⇓
4. Select Requirements	19. "Processes to Cut/Form Structural Plates and Shapes"	64. "Enterprise Product Model"	61. "Full Data Access (Read Only) to All Project Participants"
⇓	⇓	⇓	⇓
5. Select Technologies	Automated line to cut and fabricate container guide shapes	Conceptual version of integrated design and production product model CAD/CAM/CIM system	Integrated design and production CAD/CAM/CIM system with remote access capability

Table I
Industry Examples of Use of Selection Methodology

prevents duplication of data by allowing it to be entered Powrtrak allows changes made by any user to be stored systemwide [10]. This is a 'datacentric' concept, and prevents duplication of data by allowing it to be entered only one time in a power plant product model. An allied feature of the system is that any operator may view (but not necessarily change) any data in the product model.

Powrtrak overcame various constraints found in traditional design approaches. For example, in traditional approaches, elements (e.g., a pump) may be represented numerous times in various parts of the design (e.g., system diagrams, composite drawings, weight estimate and bill of materials). In the traditional approach, a change in one representation will not automatically be changed on the others, resulting in potential configuration management errors. Powrtrak ensures errors of that type are not made. Also, a designer of one system, with a question about another system, may access the other system's data. This is a version of Requirement 61, "Full data access (read only) to all project participants." An example of the effect of Powrtrak, is that a 400-megawatt fossil-fuel and pulverized-coal power plant that would have taken 60 months to design and build before Powrtrak can now be finished in 29 months [8].

Powrtrak and other software innovations at Black and Veatch are credited with boosting the company's revenue from $277.7 million in 1988 (when Powrtrak was implemented) to $693.4 million in 1993. The software helped the company submit lower bids (increasing margin in its industry), snare new business and boost market share [8].

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

In the course of carrying out the Phase II effort, the PROJECT Team concluded that:

- CAD/CAM/CIM is necessary for U.S. shipyards to become competitive with overseas yards.
- Involvement of upper management is key to ensuring that CAD/CAM/CIM is implemented in a way that will best meet a shipyard's business goals.
- A business strategy is necessary in order to provide a framework within which to select the requirements of a CAD/CAM/CIM system that is best suited for a given shipyard.
- A set of requirements can describe the elements necessary for a competitive, future-oriented shipbuilding design and production CAD/CAM/CIM system.
- Participation in multi-organizational projects, such as NSRP projects, MARITECH projects, and the development of STEP, can help shipyards enhance their competitive position.

Recommendations

The Project Team recommended that shipyards implement CAD/CAM/CIM and that upper management is involved in the implementation process. While technical expertise resides in the middle management, line management, professionals and production personnel, the drive, guidance and support must originate at the top. The Project Team recommended that upper management's involvement include becoming familiar with relevant CAD/CAM/CIM issues at the executive level, learning

how CAD/CAM/CIM can help meet a shipyard's business objectives, developing their shipyards' business strategy, and supporting the efforts of other shipyard management and technical personnel in selecting and implementing CAD/CAM/CIM in their yards. The Team recommended shipyard participation in multi-organizational projects. Finally, the Team recommended that shipyards balance CAD/CAM/CIM development within and outside the shipyard. Most yards will find it most effective to use commercial off-the-shelf programs, tailoring those programs to a small extent to suit unique needs of their shipyard situation.

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APPENDIX - LISTING OF REQUIREMENTS GROUPED INTO GENERAL AND DETAILED CAD/CAM/CIM AREAS

GENERAL AREA	DETAIL AREA	NO.	REQUIREMENT NAME
DESIGN	Conceptual/Preliminary Design	1	Concept/Preliminary Design Engineering Analysis Tools
		2	Reusable Product Model
		3	Develop Initial Build Strategy, Cost and Schedule Estimates
		4	Classification/Regulatory Body and Owner Compliance Support
	Functional Design	5	Connectivity Among Objects
		6	Tools to Develop Standard Parts, Endcuts, Cutouts and Connections
	Detailed Design	7	Automated Documentation
		8	Detail Design Engineering Analysis Tools
		9	Design for Fabrication, Assembly and Erection
		10	Linkage to Fabrication Assembly and Erection
		11	Automatic Part Numbering
		12	Interference Checking
		13	Linkage to Bill of Material and Procurement
		14	Weld Design Capability
		15	Coating Specification Development
		16	Definition of Interim Products
		17	Consideration of Dimensional Tolerances
		18	Context-Sensitive Data Representations
PRODUCTION	Fabrication Processes	19	Processes to Cut/Form Structural Plates and Shapes
		20	Documentation of Production Processes
		21	Information Links to Production Work Centers
		22	Piece and Part Labeling
		23	Creation of Path or Process Programs for NC Machines and Robots
		24	Development of Interim Product Fabrication Instructions
		25	Simulation of Fabrication Sequences
	Joining and Assembly Processes	26	NC Programs for Joining and Assembly
		27	Automated Subassembly/Assembly Processes

APPENDIX (Continued)
Listing of Requirements Grouped into General and Detailed CAD/CAM/CIM Areas

GENERAL AREA	DETAIL AREA	NO.	REQUIREMENT NAME
PRODUCTION	Joining and Assembly Processes	28	Programmable Welding Stations and Robotic Welding Machines
		29	Location Marking for Welded Attachments
		30	Definition of Fit-Up Tolerances
		31	Control of Welding to Minimize Shrinkage and Distortion
		32	Programming for Automated Processes
		33	Definition of Fit-Up Tolerances for Block Assembly Joints
	Material Control	34	Capabilities for Material Pick Lists, Marshaling, Kitting and Tracking
		35	Tracking of Piece/Parts Through Fabrication and Assembly
		36	Communication of Staging and Palletizing Requirements to Suppliers
		37	Documentation of Assembly and Subassembly Movement
		38	Handling and Staging of In-Process and Completed Parts
	Testing and Inspection	39	Testing and Inspection Guidelines
OPERATIONS MANAGEMENT	High-Level Resource Planning and Scheduling	40	High Level Development of Build Strategy
		41	Order Generation and Tracking
		42	Performance Measurement
		43	Production Status Tracking and Feedback
		44	Inventory Control
		45	High Level Planning and Scheduling
	Production Engineering	46	Development of Production Packages
		47	Development of Unit Handling Documentation
	Production Engineering	48	Parts Nesting
		49	Development and Issue of Work Orders and Shop Information
	Purchasing/Procurement	50	Material Management
	Shop Floor Resource Planning and Scheduling	51	Provision of Planning and Scheduling Information to Shops
		52	Work Order/Work Station Tracking and Control
		53	Detailed Capacity Planning for Shops and Areas
		54	Collect and Calculate Costs for a Major Assembly

APPENDIX (Continued)
Listing of Requirements Grouped into General and Detailed CAD/CAM/CIM Areas

GENERAL AREA	DETAIL AREA	NO.	REQUIREMENT NAME
UMBRELLA	Umbrella	55	Datacentric Architecture
		56	Computer-Automated as Well as Computer-Aided
		57	Interoperability of Software
		58	Open Software Architecture
		59	Accessible Database Architecture
		60	Remote Networking Capability
		61	Full Data Access (Read Only) to All Project Participants
		62	Assignment of Data Ownership
		63	User-Friendliness
		64	Enterprise Product Model
		65	Integration With Simulation
		66	Information Management
		67	Scalability
		68	Transportability
		69	Configuration Management
		70	Compliance with Data Exchange Standards

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Equipment Standardization Under Acquisition Reform

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ABSTRACT

This paper discusses the ramifications of current Department of Defense (DoD) Acquisition Reform policies on Navy equipment standardization initiatives and provides an overview of the objectives and benefits of making "best value" end item selections during the design and construction process. The DoD initiative to implement acquisition reform by changing the processes by which defense system and equipment requirements are defined and communicated to contractors is having significant impacts on equipment standardization programs. The emphasis on the use of non-developmental and commercial-off-the-shelf items (NDIs/COTS) combined with naval ship system and equipment requirements being expressed primarily in performance terms creates the potential for the introduction of large numbers of commercial equipment to the supply support system. Approaches to maximizing equipment standardization efforts in the era of commercial-based acquisition strategies are described and examples of standardization approaches using recent ship acquisitions (Strategic Sealift, LHD 1,DDG 51, and LPD 17) are presented.. Possible approaches for the use of performance-based equipment databases and real-time linkages through the Internet with COTS manufacturers are discussed. Impacts that could change the structure of existing logistics support systems and result in substantial improvements in both cost and performance of shipboard equipment and components are addressed.

LIST OF FIGURES

INTRODUCTION

U.S. Navy program managers are finding themselves increasingly under pressure to try new approaches to ensure that their programs are responsive to acquisition reform initiatives. From eliminating or greatly reducing military specifications and standards from design specifications and drawings (1,000 reduced to 143 in the LPD 17 contract design), to distributing streamlined requests for proposals, contracts and contract data requirements electronically (i.e. paperless) over the Internet, the times and the processes by which weapon systems are being procured are drastically changing. "Reinventing Government" initiatives such as the Federal Acquisition Streamlining Act (FASA), which has raised the ceiling for direct purchasing from $25,000 to $100,000, and the Federal Acquisition Computer Network (FACNET), are strong examples of how significant change is being implemented at all levels of the Government acquisition process [1]. Virtually all previous acquisition processes and practices have been under the microscope during the past two years, and those where no value added could be demonstrated have been eliminated. New thinking is encouraged and any and all ideas that may result in reduced acquisition and life cycle costs are being seriously entertained by acquisition program managers.
As witnessed by the DoD/ARPA's's two year acquisition phase Arsenal Ship Program and current planning for the SC 21 Program, gone are multi-year preliminary and contract design phases where NAVSEA design teams supported by contractors would develop extensive (often 1-2 thousand pages) "how to" design specifications with dozens of detailed contract and contract guidance drawings. Existing systems structured for risk avoidance are transforming to a process of risk management that affects all aspects of the weapon systems and platform acquisition process.

Caught squarely in the middle of the acquisition reform process is equipment standardization. For forty-five years, the goal of standardization has been to limit proliferation of items required to be supported in the Navy supply system in order to minimize integrated logistics support costs. Now, under acquisition reform, the focus is on taking advantage of the commercial marketplace, and on affordability, best value, and total ownership cost. The simple message from the Under Secretary of Defense for Acquisition Reform is, "State your requirements in performance terms and let the market respond." Developing and implementing alternatives to the traditional practices in military management and manufacturing standards allows DoD to better use the commercial marketplace and manufacturing base [2]. At the height of the Cold War in the mid-1980's, cost was merely one factor that had to be considered during the design of Navy ships. Now, with the combination of a reduced threat and declining defense acquisition appropriations,

cost, both acquisition and life cycle operation and support, is the primary consideration for acquisition and ship design managers. Cost reduction objectives of 30 percent for acquisition and 70 percent for operational and support ($4 billion target for LPD 17) is forcing NAVSEA decisionmakers to not only "think outside of the envelope," but to use "blue sky" thinking to design new types of envelopes as well. Cost trade-offs must be made at all decision making levels, including at the shipyard engineering working level. Will a $300 commercial-off-the-shelf eye wash unit/combined deluge shower work (meet the performance requirement), or is an $1,800 model required? Will a $175,000 commercial air compressor work, or is a $450,000 MILSPEC-qualified unit required to do the job? Which equipment are truly mission essential? In fact, many concepts under consideration by the SC 21 technical team question which *systems* are essential. Do equipment life cycles need to correspond to the ship's intended service life cycle, or can more affordable equipment be used and replaced periodically? Can COTS equipment and components be used to reduce acquisition costs without compromising mission effectiveness, safety, or shipboard quality of life? What are the logistics impacts of going to a total services contractor approach?

The success of the Navy's standardization initiatives under acquisition reform depend in large part on the ability of program managers, system engineers and designers to answer these types of questions. It will be the job of the cognizant shipyard systems engineer to determine the suitability of commercial equipment applications based on a demonstration of their ability to meet required form, fit, function and performance requirements. Commercial equipment that has been "marinized" may not meet stringent requirements for operation in at-sea combat conditions. Standardization metrics have consistently demonstrated that significant reductions in the proliferation of repairable items combined with commonality-based designs produce substantial cost savings over the life cycle of ships. In addition, new approaches to supply, repair part and logistics support, including total service contractors, are being tried in programs such as Strategic Sealift, and possibly in the major Navy shipbuilding programs for the next ten years, including LPD 17, Arsenal Ship and SC 21.

EQUIPMENT STANDARDIZATION

In its broadest sense, the term "standardization" encompasses a wide range of activities. Standardization includes the development of standards used in acquisitions, use of standard designs, standard administrative and logistical support procedures, and standard equipment, components and non-developmental items. Standardization is not "new business." As one Navy officer recently stated, "We're not doing new things, we're doing old things a new way." The DoD has been trying to achieve a higher degree of acquisition standardization for over forty-five years and has been successful in many cases. However, the Navy's past standardization efforts on which substantial money has been spent have often been directed at reliability problems with specific pieces of equipment [3]. Recent successes include the Navy Pump Reduction Program, the Standard Titanium Fire Pump initiative and numerous Class Standard Equipment (CSE) procurements including cranes, cargo doors and ramps for the Strategic Sealift Program. However, the Navy's Standardization Program has evolved considerably since Public Law 436, "The Defense Cataloging and Standardization Act" was passed in 1952, and now must take into account acquisition reform and commercialization.

Navy Equipment Standardization Efforts -The Defense Cataloging and Standardization Act was intended to provide an economical, efficient and effective supply management organization within the DoD through the establishment of a single supply cataloging system and the standardization of supplies. DoD Directive 4120.3M, "Defense Standardization and Specifications Program Policies, Procedures and Instructions", was developed based on the Standardization Act. In response, the Naval Sea Systems Command (NAVSEA) issued NAVSEAINST 4120.3E in April of 1986. NAVSEA has long been concerned with equipment standardization issues and took action to draft the "NAVSEA Standardization Manual," in September 1980 (NAVSEA Publication 0900-097-1010). In July 1989, the Secretary of Defense unveiled the Defense Management Report (DMR). The DMR concluded that the Government must be more disciplined in what weapons systems it buys and how they are acquired. In addition, the DMR concluded that existing government laws governing acquisition should be clarified in order to provide the DoD broader discretion in making contract awards competitively based not only on cost, but other considerations. DoD Instruction 5000.2 (dated 23 February 1991) Part 6, Section Q "DoD Standardization Program" was developed to attain the goals outlined in the DMR.

To further enhance its Standardization Program, the Navy began the process of reviewing drafts of SECNAVINST 5000.2B "Defense Acquisition", MIL-STD-680B "Standardization Program Requirements for Defense Acquisitions," and NAVSEAINST 4120.6A "Standardization of Components and Equipment" which implement the requirements of the public law, the DMR, and DoDINST 5000.2. SECNAVINST 5000.2B was issued in December of 1996, and MIL-STD-680B was approved and then canceled in June 1995 without replacement, although it may still be used for guidance. The Navy also developed a Standardization Guide Desk Book which conveys the importance of standard part/equipment selection in the design process and summarizes current policies and processes.

Other standards and guidance documents governing standardization policies and affecting standardization under acquisition reform include MIL-STD-965, "Parts Control Program," DoD Publication SD-2, "Buying Commercial and Nondevelopmental Items," and DoD Publication SD-15 "Performance Specification Guide". To comply with public law and current DoD policy, the Navy incorporates standardization initiatives into the entire life of ships, from initial design through construction, operational support, and finally, through decommissioning.

Many programs, such as the LHD 1 and the DDG 51 classes, have achieved high levels (over 90%) of standardization of HM&E repairable items [4]. The CSP/S-24 Strategic Sealift Program contract requirements call for 98% intra-class standardization as measured against the first ship of the class. The "or equal to" criteria for selection of non-standard equipment on Strategic Sealift and LPD 17 class ships includes:

- Technical performance,
- Regulatory Body approval,

- Safety, reliability and maintainability,
- Interoperability,
- Logistic support and survivability.

The success of standardization initiatives affects various Navy activities, including Planning and Engineering for Repair and Alteration Activities (PERAs), Type Commanders (TYCOMs), System Commands (SYSCOMs), In-Service Engineering Activities (ISEAs), and individual ships and the sailors who operate them. RADM R.D. Williams, III, the Navy's Deputy Director of Expeditionary Warfare, reminded the participants at the 1997 Navy Logistics Symposium in Los Angeles that the true customer when making end item selection is "the. 18, 19 and 20 year old sailors who are putting their lives on the line for their country." As described in the following sections, there are numerous DoD and DoN policy and guidance documents that describe the Program Manager's responsibilities for a wide variety of standardization programs, procedures, and initiatives. The following analysis presents the argument that successful standardization is achievable under acquisition reform because requirements stakeholders now have the information tools to take advantage of best value commercial equipment selections and options to apply alternative logistics support processes.

GOALS AND OBJECTIVES

The purpose of Navy standardization is to *reduce total ownership cost* through the selection of equipment and components of proven performance which can be fully supported within the Navy supply system or by the OEM with all necessary spare parts, test equipment, training and technical documentation. Total ownership cost includes both acquisition costs, and operating and support (O&S) costs such as crew, fuel, maintenance and training. As shown in Figure 1, there are approximately 168,000 different HM&E components in the Navy supply support system ($15 billion in Government assets) with an average of 6,000 new repairable items being added each year. The logistics support costs associated with this equipment is approximately $300 million per year. More than 50% of this equipment is installed on five or fewer ships, and approximately 15% of these are one-of-a-kind items.

Excessive quantities of one-of-a-kind and low fleet population equipment with similar functions result in unnecessary logistics support and repair costs. Since all items selected for the lead ship are intended to be standard items for the particular ship and ship class, special emphasis must be placed on determining the quality, reliability, and operational and life cycle support costs for the items selected. If a $100,000 difference exists between ownership costs for a major piece of equipment on a large class purchase such as the DDG 51, the total cost of ownership savings can quickly reach $1,000,000.

Affordability Through Commonality Program -

The primary principle of NAVSEA's Affordability Through Commonality (ATC) Program is that commonality of ship systems and interfaces, and standardization of equipment and components, are essential elements in implementing an effective design-for-affordability process. The goal of this principle is to employ the use of systems, equipment and components, both within ship classes and across ship types, that are standardized to the maximum extent practicable. As Grigg [5] notes, standardization ideas (and goals) are dependent on the expected benefit or motivation behind the standardization effort. Equipment standardization is aimed primarily at reducing logistic costs. Intra-ship standardization is aimed at increasing operational readiness by increasing the interchangeability of spare parts. The primary objectives of the ATC Standardization Program are:

- To reduce costs including manpower costs needed to operate and maintain ship systems,
- To reduce acquisition costs through the use of common Fleet-wide equipment,
- To optimize the variety of items used in logistics support in order to enhance interchangeability, reliability, maintainability, and availability;
- To improve the operational readiness of ships, and
- To ensure that products of requisite quality are procured that meet performance, form, fit, function, safety and environmental requirements.

The first tier objective is to ensure the use of common equipment for similar functions on the ship (intra-ship standardization). The second tier objective is to attain the maximum level of interchangeability of equipment and components by reducing the number of unique items installed within the ship class (intra-class standardization). The third tier objective is to obtain standardization with existing supported equipment and components in the Fleet while meeting performance and other requirements (intra-Fleet standardization). In addition, objectives at all levels include limiting the range of different types of equipment and components used, and provisioning for the maximum use of common maintenance, fault diagnostic, test and support equipment and training material.

As stated in the NAVSEALOGCEN Guide to Standardization, the benefits of maximizing the use of standard designs and equipment are intuitive. From a total ownership cost perspective, the use of standard components reduces both product acquisition and life cycle costs by:

- Allowing for economies of scale from large purchase orders,
- Minimizing the need for development of new provisioning technical documentation,
- Reducing the number of purchase orders that need to be processed,
- Reducing warehousing costs through decreased stocks of spare parts,
- Reducing required capital investment costs for developmental items, and
- Reducing the need for training associated with new equipment introductions.

BARRIERS TO STANDARDIZATION

Regardless of whether Navy standard or COTS equipment and components are selected as class standard equipment during ship design, there are numerous barriers to achieving standardization objectives, including the following:

Length of Time Between Shipbuilding Programs - A major Navy ship design and production program can take as many as ten years or more from concept to commissioning. During this

time, equipment specified for procurement may no longer be manufactured or supported by the original equipment manufacturer (OEM), and newer, more cost responsive, efficient and reliable models may become available. However, there are numerous acquisition reform and ship design improvement initiatives underway in the Navy shipbuilding community to dramatically decrease the concept to commissioning timeline.

Manufacturer Turnover - There is considerable turnover among OEMs resulting from going out of business entirely or from mergers and buy-outs. The discontinuation of manufacturing lines and cancellation of repair parts support contracts prevents effective long-term standardization.

Obsolescence - Equipment and components, and especially electrical and electronic items, are subject to obsolescence due to rapidly advancing technologies that provide increased performance and cost efficiencies.

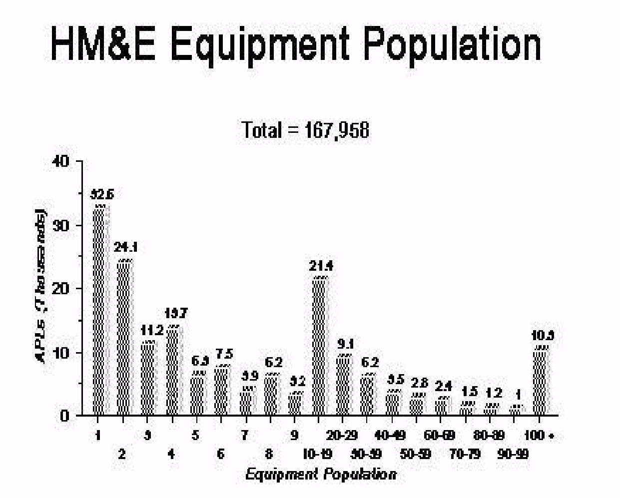

Figure 1 - HM&E Equipment Population

To a lesser extent, this is true with HM&E items as continuous improvements are made to equipment which change their configuration, and hence their technical data package, which generates a new Allowance Parts List (APL) number in the Navy logistics support system.

Lack of Acquisition Incentives - Unless a shipbuilder is contractually obligated or provided incentives to purchase standard equipment, equipment awards will go to the low bidder or to regional suppliers. In the past, this has often resulted in thousands of new items being unnecessarily introduced to the Navy supply support system. The key to maximizing standardization is to seek and obtain long term partnerships with proven quality performance OEMs and vendors who are committed to providing reliable commercial repair parts supply support.

Navy Market Share - The Navy's influence on the commercial market has been in decline for several years. Although the Navy's share of the shipbuilding market in the United States is significant, in relationship to the world market it is not. In particular, the Navy's share of the marine equipment market is not significant enough to influence many manufacturers or vendors other than those who make Navy-unique equipment such as replenishment and fueling-at-sea systems, and items built specifically for combat systems that must withstand grade A shock and meet stringent vibration requirements.

Lack of Engineering Awareness - Many working level engineers are simply not aware of the impacts of non-standard equipment selections on logistics support activities. For example, the average ILS cost for the introduction of a new pump is approximately $63,000 and this figure excludes the price of training, which can run into the tens of thousands of dollars depending on the complexity of the unit.

Lack of Data Access and Communication - In order to ensure that the maximum benefits of standardization are realized, systems engineers must have ready access to current and accurate commercial and Navy standard equipment performance, logistics and cost data that will enable them to quantifiably measure cost avoidance and projected return on investment.

TYPES OF STANDARDIZATION

Standardization is defined by the DoN's Office of the Assistant Secretary for Research, Development and Acquisition (ASN(RDA)) as the process used to achieve the greatest practicable uniformity of items of supply and engineering practices, to ensure the minimum feasible variety of such items and optimum interchangability of technical information, training, equipment parts and components. The term "standardization" means maximizing the uniformity of equipment and components used in systems to reduce total ownership costs. For the purpose of clarifying terminology, "standard" equipment can be considered from several different viewpoints.

Navy Standard Equipment - Navy standard equipment are those items for which the Navy owns all technical data rights including Level III manufacturing drawings. There are approximately forty different Navy standard equipment technical data packages. Examples of Navy standard equipment include the Standard Navy Fire Pump and the STAR low pressure air compressor. However, a major objective of acquisition reform is to reduce or eliminate the need for the Government to maintain configuration control of technical data packages such as these. Current funding levels reflect declining intent to develop new Navy standard equipment data packages.

Equipment Built To Standards - Equipment may be built specifically to meet either Military (MILSPEC) or commercial (ASTM/ANSI) standards. However, under acquisition reform initiatives, the use of MILSPEC equipment is limited to applications where no commercial alternative exists, where use of the commercial equipment is not the most cost responsive approach, or where the MILSPEC equipment is the commercial standard. DoD Directive 5000.2 provides clear direction in terms of the use of commercial and non-developmental items. The Directive states that non-Governmental standards and commercial item descriptions must be used in preference to Federal and military specifications and standards whenever practicable. The Directive's mandate for the use of non-developmental items is that they should be incorporated into the design and development process consistent with operational requirements. A key element of this approach is to ensure that market research and analysis is conducted to determine the suitability and availability of an item

prior to the commencement of a developmental effort. Compounding this problem, there is a real scarcity of commercial standards that apply to marine industry equipment and components.

Standard (supported) Equipment - Standard equipment is any equipment listed in the Navy's Hull, Mechanical and Electrical Equipment Data Research System (HEDRS) database that has already been through the logistics provisioning process and is still supported by the OEM. Standard equipment may be built to either military or commercial standards, and in many cases, the military standard is the commercial standard. However, due to the large numbers of one-of-a-kind equipment in the Fleet, special preference should not necessarily be given to standard equipment over COTS equipment unless the total ownership cost analysis indicates the standard equipment to be the best value selection for the Government. Items listed in the HEDRS database are considered non-developmental items, but not necessarily COTS.

New Commercial Standard Equipment - Use of COTS items may be necessary and/or desirable under certain circumstances, including when:

- There is no standard equipment or component available that meets the performance requirements,
- Specified performance requirements cannot be modified to allow use of standard components,
- Suitable standard equipment or components cannot be supplied in time to meet ship construction schedules, and
- A total ownership cost analysis indicates that a new commercial item would provide significant design and cost advantages without compromising performance, or form, fit and function requirements.

NAVY NDI/COTS POLICY

The Acquisition Reform Office (ARO) of the DoN is the focal point for matters pertaining to the management and execution of the Navy Acquisition Reform Program. The ARO provides counsel to the ASN(RDA), and coordinates various DoN Acquisition Reform Program initiatives. The underlying objectives of the Navy's ARO are to reduce costs of DoN acquisition and ownership, reduce the cycle time between identification of requirements and delivery of products, and transition to an integrated national industrial base sustained predominately by commercial activity which is capable of providing superior military products of high quality.

The ARO philosophy for achieving acquisition reform is to re-engineer the process by which the DoN conducts business. This re-engineering is the focus of the acquisition reform program. The ARO defines acquisition reform as "a program to achieve DoD's military superiority objective at reduced cost with increased responsiveness to customers." Key elements of the ARO's strategy are to integrate the military and commercial industrial base, increase innovation, foster managed risk, encourage empowerment, and establish cross-functional teams using world-class commercial practices. The ARO defines their mission as nothing short of "changing the culture of the current acquisition environment to give program managers the freedom to succeed". The ARO vision is that this fundamental cultural change will be supported by world class communications that allow exploiting the proliferation of information technologies and allow real-time participation in innovative product and process demonstrations. The ARO also envisions virtual workplaces where new process concepts are tested and applied to programs and "exploitation" of modeling and simulation technologies including high performance computing, high bandwidth networks and large object-oriented databases. The objective of the ARO's philosophy is to achieve "world class" status in both acquisition processes and the products that are procured. A key element of the new DoD acquisition culture is that it is dynamic in nature: The ARO states that organizational and management structures will be used to continually adapt processes and methods to match changing demands, and that management networks will be used to collaborate interactively among supplier, producer, and customer teams to create world class products and services.

The Federal Acquisition Streamlining Act requires that in defining requirements, preference must first be given to the use of commercial items, and second to the use of other types of non-developmental items. The overarching goal of Navy policy on the use of COTS and NDIs is to use commercial items to fill requirements to the greatest extent practicable. The Supportability Policy for Navy Implementation of Department of Defense Acquisition Reform initiatives recognizes the difficulty in achieving standardization under acquisition reform: "Achieving standardization is often in direct opposition to the use of performance specifications and commercial-off-the-shelf items. It is necessary to obtain a balance between these two ends of the spectrum by using good business and technical judgment in determining the best approach to reduce the total cost of ownership." In addition, the policies governing existing approaches to equipment procurement recognize the need for innovative approaches to logistics support. The Navy Guide to Standardization recognizes the difficulty of standardization under acquisition reform, but is firm in its conviction that it is achievable. The guide states that achieving standardization and using NDI/COTS equipment can be accomplished together in the same acquisition, but that the Program Manager must resolve all supportability issues before selecting an NDI/COTS equipment. Resolving these issues assures the Program Manger of achieving standardization and NDI/COTS requirements, and meeting the needs of the Fleet. Supportability includes the capability to purchase the item from the manufacturer now and in the future, and providing support to Fleet users of the item whenever and wherever support is required. It is the Program Manager's responsibility to analyze the acceptability of the performance of the item, the item's total life cycle cost, and the cost effectiveness to the Government.

Elements of Effective Standardization - The ATC Standardization Team has identified four primary keys to successful standardization. The first is that effective equipment, component and piece part standardization begins with the working engineer who is responsible for requirements definition and equipment selection during the design phase of the ship acquisition process (***buy the right one first***). The second is that maximizing the benefits of equipment standardization requires long term commitments to original equipment manufacturers who both warrant and agree to support their products and provide commercial logistics support as ***needed (Quality partnerships)***. Innovative quality partnerships such as the Naval Material Quality Assessment Office's "Red/Yellow/Green" Program, where the Government works with vendors to improve quality, combined with long term vendor/supplier relationships are essential ingredients to successful equipment standardization under acquisition reform. The third is that the use of equipment packaged units and modules comprised of standard equipment families will accelerate the return on investment from standardization initiatives (***economy of scale***). The fourth is that the use of electronic tools such as NAVSEALOGCEN's HEDRS, Product Deficiency Reporting Evaluation Program (PDREP), Open Architectural Retrieval System (OARS), Configuration Data Managers Database Open Architecture (CDMD-OA), and NAVSEA's Ship Equipment Attributes - Logistics Information Network (SEA-LINk) are essential tools for efficiently and accurately identifying, locating and communicating end item design and procurement data (***who's selling what, how good is it, can it be supported long term, and does it reduce ownership costs?***).

Performance Requirements \ COTS Candidates	Marconi	Interstate	Matnavox #1	Matnavox #2	Motorola	Collins #1	Collins #2	Stanford	Texas Instr.	Tracor	Trimble Navpak	Remarks
Battery Power	√	√	√	√	√	√	√	√	√	√	√	* Add-on
Waypoints	x	√	√	√	x	√	x	√	√	√	√	
MGRS	x	√	√	√	√	√	x	x	√	x	√	
Lat/Long	√	√	√	√	√	√	√	√	√	√	√	
UTM	√	√	√	√	√	√	x	√	√	√	√	
SEP<100M	30	51	100	17	25	16	25	14	16	100	43	accuracy
<10 lbs.	5	10	9.5	29	7	17.5	9.9	7.5	9.8	7.7	5	weight
User Friendly	x	x	√	√	√	x	√	√	√	√	√	field test
Self Training	x	x	√	√	√	x	√	√	√	√	√	field test
25m/sec	?	√	√	√	√	√	√	√	√	√	√	
5 m/sec²	?	√	√	√	√	√	√	√	√	√	√	
Built-in-Display	√	√	√	√	x	√	√	√	√	√	√	
Malfunc. Ind.	?	√	√	√	√	√	x	√	√	√	√	
160 º Conical	?	√	√	√	√	√	√	√	√	√	√	
Cost	?	$9.5K	$4.9K	$7.8K	$10.0K	$24.5K	$14.0K	$20.0K	$15.0K	$9.7K	$4.7K	

Legend: √ = Meets requirement x = Does not meet requirement ? = Information not provided

Figure 2 - COTS Market Survey

Non-developmental Items - "Non-developmental item" is a statutory term describing items that have been previously developed for production. Any previously developed item used exclusively for government purposes by a Federal agency, a State or local government, or a foreign government with which the U.S. has a mutual defense cooperation agreement, is considered an NDI. For example, the mechanical dereefer used with the U.S. Army's cargo parachutes was developed for and first used by the Canadian army. Non-developmental items (NDIs) include items previously developed for use in the Fleet or by other DoD activities and Government agencies. NDIs include items obtained from a domestic or foreign commercial marketplace.

Commercial Items - Commercial items are defined as "any item, other than real property, that is of a type customarily used for non-Governmental purposes, and that has been sold, leased, or licensed to the general public, or has been offered for sale, lease, or license to the general public" [6]. An item is considered a "commercial" product if it is customarily used by the general public and has a commercial sales history, is listed in catalogs or brochures, has an established price and is readily available to the general public. New items that have just been introduced to the market and items that are intended to be available at the time of ship construction are considered commercial items as well. Commercial items can also be the product of integrating commercial subsystems and components into unique systems. Industrial plant equipment that combines commercial components into a unique system based on the Navy's needs is one example, as is a computer system comprised of commercial subsystems that are integrated into one system.

The Program Manager's Role - The Program Manager's role in implementing commercial standardization strategies under Acquisition Reform is critical in determining the extent that NDI/COTS are applied throughout the acquisition process. The ARO emphasizes that Program Managers must incorporate effective communications networks to optimize their Integrated Product Team's (IPT) ability to analyze the total operational and support life cycle impacts of using a COTS item [7]. In addition to assessing factors such as environmental impacts and costs of disposal, IPTs are required to determine which item or items meet logistics support program plan requirements and to determine the cost benefits to the Government. The IPTs must identify one-to-one equipment substitution where COTS items meet specified form, fit, function and performance requirements, *and* consider if a commercial item can be modified to meet the requirements. IPTs must also consider if the requirements themselves can be adjusted to accommodate use of the item without significantly degrading overall system performance. The Navy Standardization Guide addresses this issue by advising that if no COTS equipment is

suitable, then the issue of modifying an existing commercial item must be addressed. Any use of COTS items or modified COTS items may also result in the Program Manager having to reduce or relax (i.e., trade-off) non-critical requirements in order to increase the pool of qualified, available COTS items. Some COTS items such as workshop equipment are already developed for heavy-duty industrial applications and harsh environments and often meet specified requirements without modification, including stringent shock and vibration standards.

The DoD Acquisition Management Policies and Procedures states that programs using commercial systems or equipment should make maximum use of existing logistics support and data. Development of new organic logistics elements will be based on critical mission need or substantial cost savings, or both. The DoD acknowledges that it may be necessary to modify existing logistics support procedures to allow for maximum use of COTS items. This approach necessitates innovative repair parts supply concepts to be developed that support accelerated integrated logistics planning schedules and require acquisition techniques such as buyouts, warranties, and data rights escrow in order to mitigate technical and support risks. Commercial logistics support also requires long term (at least the life cycle of the equipment) vendor contracts to ensure adequate sparing for items not in the Navy supply support system.

BEST VALUE EQUIPMENT SELECTION

The first step in completing a best value equipment analysis is to identify the COTS items that are readily available on the market that meet the required performance characteristics. This requires an in-depth market survey using a methodology similar to that shown in Figure 2 for a Global Positioning System. In order to be in compliance with acquisition reform directives, particular care must be taken to avoid listing "how to" design requirements and to include only performance, form, fit and function requirements. However, a short term increase in the numbers of COTS items that become "new standard" equipment requiring support may be necessary in order to obtain long term reductions in the total numbers of different APL-worthy items in the Navy supply support system.

Although it is clear that acquisition reform policy makes COTS items the first order of preference, the selection of COTS equipment is not necessarily the best value equipment option for the Government. Cost avoidance from the procurement of functionally interchangeable commercial HM&E equipment is equal to the actual savings resulting from the least cost equipment procurement minus the costs incurred from increased logistics and infrastructure support of the additional item.

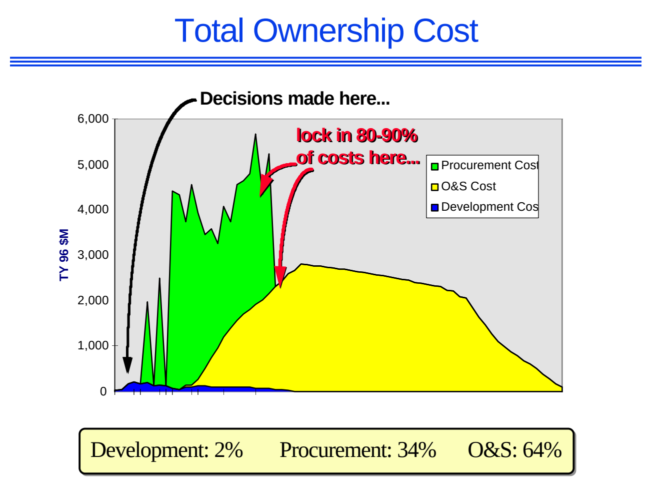

Figure 4- Total Ownership Cost

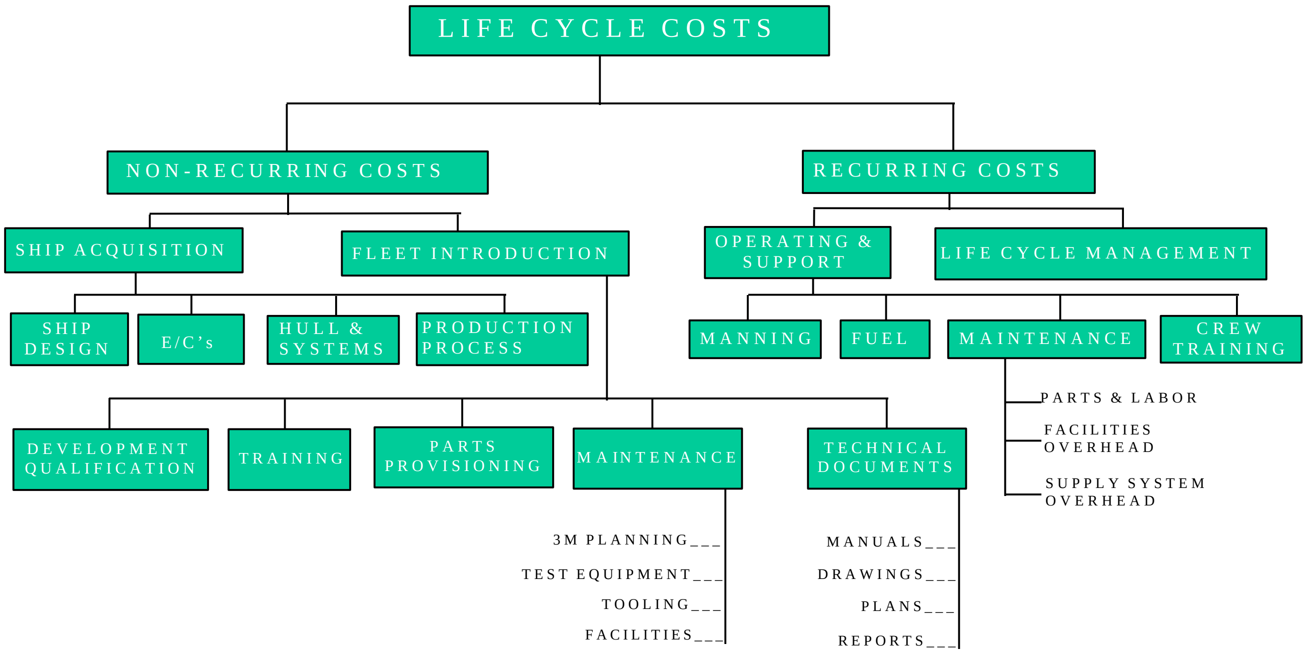

Figure 3- Life Cycle Cost

Life Cycle Costs - As illustrated in Figure 3, NAVSEA 017 considers two types of life cycle costs (LCC); Non-Recurring Costs, and Recurring Costs. Non-recurring costs include factors such as the cost of the ship design, parts provisioning, and purchasing technical manuals and test equipment. Recurring costs include factors such as manning, fuel, crew training, maintenance and repair.

Total Ownership Cost - Initial acquisition cost is only one of many factors that need to be considered in making equipment selection decisions**.** As shown in Figure 4, the majority of total end item costs are incurred during the operational and support phases of an equipment's life cycle. The initial development and procurement cost of a repairable (maintenance-significant) end item typically comprises only about 36% of the total ownership cost (TOC) with the remaining 64% accrued during the operational and support phase of the item. As a result, 80 to 90 percent of an item's TOC is determined prior to ship deployment. In order for reductions in TOC resultant from standardization to be calculated accurately, the costs associated with the different phases of an acquisition project, from concept development through crew training, maintenance and logistics support need to be considered [8]. True TOC also includes the cost of end item disposal as well. Standardization of NDI and COTS items can contribute significantly to reducing TOCs, including:

- Maintenance and repair parts costs (fewer support parts are needed),
- Stowage costs (fewer Coordinated Shipboard Allowance List (COSAL) items onboard),
- Training costs are reduced (interchangability is enhanced and fewer items are required to be purchased for training purposes),
- Provisioning and administrative and management costs (fewer supply support items need to be procured and fewer APLs and NSNs need to be developed and maintained),
- Configuration control costs (fewer types of items need to be tracked),
- Installation and interface control drawing maintenance costs (fewer drawings), and
- Provisioning costs (fewer numbers of provisioning parts technical packages need be prepared).

Affordability Analysis Methodology - There are numerous measures of affordability including average acquisition cost, life cycle cost, acquisition rate, discounted and non-discounted affordable fleet size, and force levels for specified budget and ship life. Rains [9] has outlined an effective approach for cost analysis methodology within which standardization

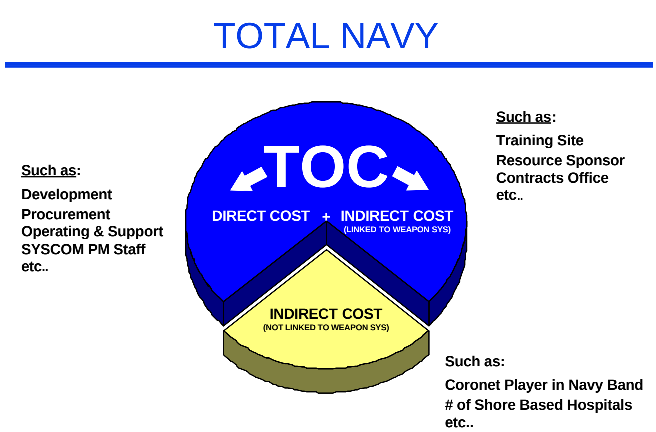

Figure 5 - Direct and Indirect Costs

affordability factors can be considered. Affordability analysis for equipment standardization requires considering TOC as a set value for each equipment when used in the analysis.

Specific Cost Factors - Optimizing equipment operating economies is a central element of achieving effective standardization. Life cycles of equipment typically range from a minimum of five years to as many as forty years (the ship's life cycle). Factors such as the cost of maintenance-significant piece parts (especially those designated for inclusion on the COSAL), the cost of provisioning, and the cost for National Stock Number (NSN) maintenance must be considered during the equipment selection process. Direct and indirect life cycle support cost percentages are illustrated in Figure 5.

In addition to acquisition costs, the following ILS elements must be considered in the total cost of ownership equation (as applicable to the specific equipment under consideration for standardization and tailored to the particular acquisition strategy):

Cost of Provisioning - Provisioning is the process of developing support for new equipment and consists of cataloging parts, procurement of supply support items, developing maintenance philosophies and computerizing support data. The data developed during provisioning is used to develop an Allowance Parts List (APL) which describes required maintenance and parts support. A National Stock Number (NSN) is assigned to the item and an annual cost of management for maintaining the item in the Government supply system is assigned by NAVSEALOGCEN.

Cost of National Stock Number (NSN) and Allowance Part List (APL) Maintenance - The cost of NSN and APL number maintenance is related to the administrative and management costs associated with maintaining the supply support system. This cost is dependent on the type of equipment (its complexity) and the projected life cycle (duration) over which the item will be required to be tracked by the system. The average cost of maintaining an item in the supply system is approximately $500 per year.

Cost of Training - Training costs include costs for students, instructors, training aids, tools, and support equipment, and costs associated with course materials, training site operation, and travel and administration. In addition, the cost of technical review of new course material and liaison with manufacturing representatives must be accounted for. The Management Consulting Directorate of the Office of the Auditor General of the Navy estimates this cost to be at least $2,000 per item. Training costs also can impact procurement if one or more items require purchasing for land-based training facilities.

Cost of Installation Drawing Changes - Variations in form and fit between the original standard or installed equipment and the COTS item may result in the need to modify installation control drawings. The cost of installation control drawings is estimated to be $1,000 per item by NAVSEALOGCEN.

Cost of Technical Manuals - The practice of developing technical manuals in accordance with a strict, Government-only Contract Data Requirements List (CDRL) is gradually giving way to the acceptance and use of COTS technical manuals except for Navy-unique developmental items and systems. For the purpose of calculating COTS technical manual costs, $0 is assumed to be applied.

Cost of Planned Maintenance - The life cycle cost of planned maintenance is estimated by NAVSEALOGCEN to be an average of $500 per equipment.

Cost of Planned Repairs - The cost of planned repairs due to piece part replacement is dependent on the inherent reliability and mean time between failure for each item and must be calculated independently to determine a value for the equipment under consideration for standardization.

Cost of Disposal - The estimated cost of disposal of the end item must also be considered in determining ownership costs, especially costs associated with disposal of any hazardous wastes that may be required.

Cost of Configuration Control - Configuration control cost includes identification of equipment for COSAL development and is dependent on the complexity of the item. For example, the configuration control cost could be as low as $164 for a capstan, and as high as $5,372 for a circuit breaker. Configuration control costs are even higher for more complex equipment.

STANDARDIZATION TOOLS

NAVSEA ship design managers and system engineers must have timely and rapid access to logistics cost data and analysis information that are necessary to successfully obtain the balance between traditional standardization objectives (minimizing the proliferation of items that need support) and standardization under acquisition reform (taking advantage of commercial market technologies and attractive procurement opportunities). The need for an extensive equipment design and life cycle cost information database recommended by Dickenson [10] has now become a reality as NAVSEA and NAVSEALOGCEN have both launched highly effective online equipment information database systems. Due to the large numbers of items and equipment subject to standardization and commonality, access to various database systems is required to provide critical component performance characteristics, logistics and cost information to the cognizant engineer. A typical Navy combatant has approximately three to four thousand different types of repairable equipment installed. Tools such as the Internet are now increasing the ability of designers, logisticians and purchasing department personnel to rapidly obtain accurate product data. As described in the following paragraphs, the primary database tools currently being used are HEDRS, PDREP, CDMD-OA, OARS and SEA-LINk, each of which provides critical information to the equipment selection decision maker.

Hull, Mechanical and Electrical Equipment Data Research System (HEDRS) - The Navy's primary tool for accomplishing HM&E Standardization during the 1990's has been HEDRS, developed and managed by NAVSEALOGCEN. The HEDRS database is an unclassified Compact Disk-Read Only Memory (CD-ROM) listing of approximately 168,000 HM&E items installed in the fleet. All of the equipment listed in HEDRS are NDI. HEDRS is a compilation of databases that consists of four parts:

(1) A Components Characteristics File (CCF),
(2) An Equipment Applications File,
(3) A Supportability Database, and
(4) An Integrated Logistics Support Database.

The ILS database function of HEDRS reports whether ILS data has been developed for the particular equipment. HEDRS also contains data regarding equipment fleet populations and is scheduled to include average repair and maintenance cost data in its next release. The CCF describes form, fit and function

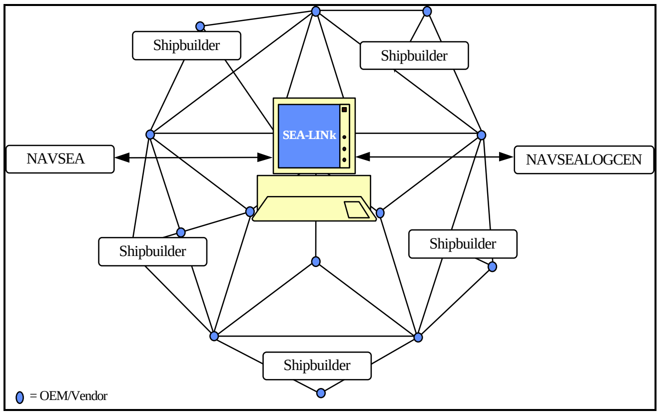

Figure 6- SEA-LINk Electronic Network

attributes and is indexed by APL numbers. The equipment applications file documents where within a particular ship the equipment is installed. Supportability information is derived from a manufacturers survey conducted every two to three years and is expressed in terms of an Engineering Support Code (ESC). An ESC of "A" means that the item is fully supported by the manufacturer for both initial procurement and for repair parts. An ESC of "B" means that the end item is obsolescent (is no longer supported or cannot be procured).

Product Deficiency Reporting Evaluation Program (PDREP) - PDREP is a NAVSEALOGCENDET Portsmouth, New Hampshire, centralized reporting system which provides quality assurance data collected from all Navy SYSCOMs. The PDREP system contains deficiency reports on new and newly reworked material, relevant contractor evaluation data and contract information, surveys and test reports. The system allows users to generate Contractor Evaluation System (CES) and Quality Deficiency Reports (QDR). PDREP uses a "Red/Yellow/Green" ranking system to identify manufacturer quality deficiencies.

Configuration Data Managers Database Open Architecture (CDMD-OA) - CDMD-OA is a NAVSEA 04TD initiated data system developed to allow shore- based Configuration Data Managers (CDM) to track the status and maintenance of naval equipment and their related logistics items (drawings, manuals, etc.) on ships and naval activities around the world. The purpose of CDMD-OA is to reduce the dataflow lag time between the ship, the CDM, and the Naval Inventory Control Point. CDMD-OA uses INMARSAT satellite transmissions and high speed Internet connections via the NAVSEA Enterprise-Wide Network (NEWNET). CDMD-OA provides a single repository of all Naval configuration and logistics data from around the world.

Open Architectural Retrieval System (OARS) - OARS Version 2.1 was released in May of 1996 and is a Windows-based, desktop tool developed by NAVSEALOGCEN which allows NAVSEA engineers to quickly and easily generate standard and ad hoc reports. The types of reports include the Parts Issued for Maintenance Detailed Report, Ships' 3-M History, and System Performance and Readiness Improvement Through Technical Evaluation Reports. OARS can access any Structured Query Language (SQL) compliant database and obtains its data from both the Ships' 3-M and PDREP systems. Future versions of OARS will provide direct access to the PDREP and CDMD-OA systems.

Ship Equipment Attributes - Logistics Information Network (SEA-LINk) - SEA-LINk development has been supported by Advanced Marine Enterprises and NAVSEA 03R3's ATC Program. SEA-LINk is primarily an equipment information database and systems engineering tool. Its purpose is to aid ship design and acquisition teams in the selection of equipment, systems, and components based upon best performance, cost, quality, and logistics supportability. SEA-LINk was developed specifically to address acquisition reform objectives by matching performance requirements with standard and COTS items. It also provides critical cost and logistics information necessary to make "best value" equipment and end item selections during the design and acquisition process. Essential form, fit, function and performance requirements can be listed and "compared" using the "compare to" function with both Navy supported and COTS items contained in the master database. The SEA-LINk system contains unclassified data from the HEDRS, PDREP, CDMD-OA and OARS systems. In addition, SEA-LINk has information regarding COTS equipment, including acquisition and logistics data such as NSN replacement costs and COSAL data. The SEA-LINk system can be used as an effective configuration management tool and was also built with "hotlinks" to manufacturers' Internet and WWW sites to foster quick communication between system engineers and the commercial world. As shown in Figure 6, it is envisioned that SEA-LINk will become an integral component of an electronic (Internet-based) network of shipbuilding data and also be accessible on the NAVSEA Local Area Network (LAN).

DESIGN STANDARDIZATION

An effective means to foster standardization under acquisition reform is to provide design team personnel with clearly defined constraints and selection criteria for use throughout ship design, and to monitor the use of those constraints and selection criteria. Design constraints and selection criteria may include a listing of items that meet design standardization criteria and may also take the form of uniform space allocations and standard interfaces and restrictions upon the population of items available to perform a given function.

Standardization Design Reviews - Standardization personnel should perform standardization design reviews to oversee the requirements for the selection of items developed in accordance with the provisions of the Logistics Support Standardization Plan and to ensure the integrity of that selection throughout the design and procurement process. Standardization reviews should be conducted to ensure that all equipment and components performing a similar function are screened with a view towards settling on a single make and model to perform as many like functions as possible in as many systems as is practicable. If engineering and cost analysis indicates that the available standard is not the best or most effective design choice, non-standard NDI should be used. Nonstandard COTS equipment should only be used for applications where use of the item will significantly reduce total ownership cost through lower acquisition cost, superior reliability and maintainability performance, reduced manning, or some combination of these factors. However, before selecting a COTS item, the cognizant engineer should ensure that there is no standard equipment available which meets the specified performance/design/support requirements that is as attractive from a TOC perspective. Selection of a nonstandard equipment should

offer a significant advantage over all available standard equipment.

Modular Design and Equipment Packaged Units - The objective of applying modularity to the design and construction of ships is to reduce acquisition and total ownership costs through application of fewer, standardized system designs. It is intended that the use of modular construction methodologies will result in improved efficiency in the construction process by reducing the time required for design team efforts, simplifying design methodologies, and minimizing custom design research and development efforts. Modular design and construction methodologies should be used wherever they can be applied to standardize equipment arrangements, space allocations, and system interfaces.

Although it means different things to different people, as used herein the term "modular construction" means designing and fabricating spaces, compartments, systems, or equipment packaged units that represent a grouping of functionally or operationally related items. Modular construction is characterized by the use of standardized structural systems architecture integrated with common equipment, components and piece parts. Module components may be structural elements, such as standardized panel sizes used repeatedly in the fabrication of bulkheads, or standardized units and components grouped and assembled with others of a like kind. Modular-based approaches to standardization provides commonality with other systems and auxiliary service and distributed system interfaces. Modules may take the form of stand-alone, space, compartment, or system modules comprised of standard and common equipment, components, piece parts and auxiliary service interfaces that perform specific functions. Generally, modules are ready for installation, hook-up and operation, or in some cases, may resemble a packaged equipment unit constructed or assembled on a common subbase or foundation comprised of functionally related, standardized equipment and components ready for installation. The vision for the use of module construction and integrated product databases is shown in Figure 7.

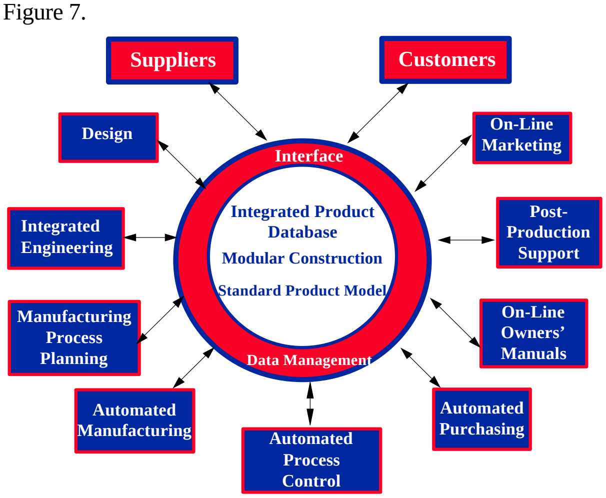

Figure 7- Integrated Product Database

Examples of modules include the ATC-developed crew sanitary space, reverse osmosis, and fire pump modules. Modules are indicative of integrated design solutions that maximize efficiencies that result from applying standardized architectures during ship design and construction. Modular construction and fabrication techniques share the following common elements:

- Capability to be assembled independent of the mainstream ship construction process,
- Comprised of standardized equipment, components and piece parts,
- Are interchangeable with other modules of a like kind,
- Use a common foundation, subbase, skid, or other means of structural support,
- Use common interfaces for shipboard hook-up to distributed services.
- Can be lifted and transported intact to the final installation location, and
- Can be tested off-ship in a commercial facility or workshop environment.

Although using common modules across the fleet restricts optimization of design features for a particular ship design [11], the cost advantages far outweigh the performance tradeoffs. The key elements of effective standardization of module equipment and components is that the final installed product *be **affordable, producible, testable, reliable, maintainable, supportable, and upgradable.***

SUMMARY

Standardization under acquisition reform is requiring Navy design and engineering personnel to use new approaches to requirements definition (performance oriented) and equipment selection and life cycle support processes (commercial supply support - quality partnerships with OEMs/vendors). Applied information technologies are increasingly being used to determine best value and total return on investment for COTS items that meet performance requirements. This electronic distribution and dissemination of equipment information now allows NAVSEA to conduct comprehensive market research to determine best value and optimum total ownership cost for many end items. New approaches to computer-aided acquisition and logistics support and a growing awareness that many COTS items are superior (and have reduced acquisition and operating and support costs) to "standard" items are also opening the doors to increased use of a wide range of commercial items. However, preference for use of COTS items does not mean that they should be used in all applications, only ***where it makes sense from a performance and total ownership cost standpoint.***

The use of Integrated Product and Process Teams will result in fewer opportunities for missed or misunderstood communication of equipment and weapons system performance requirements. As NAVSEA takes its position within this new paradigm, a partnership with industry becomes possible as both customers and suppliers strive towards a common set of goals: increased quality and lower total ownership cost. Alternative approaches to integrated logistics and supply support are being implemented as evidenced by the fact that program managers are actively considering contracting with shipbuilders for total ship life cycle support (total services support contracting). Additional benefits of standardization under acquisition reform include greater availability and lower unit prices for equipment and components. DoN requirements that are integrated into commercial production are far more likely to have a stable industrial base to draw from, should there be a need to during time of war. Meeting

standardization goals under acquisition reform is achievable when cognizant personnel are able to apply the newly available technologies and approaches to product acquisition and support that are changing the way the DoN conducts business.

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An Integrated Approach For The Computerized Production Process Of Curved Hull Plates

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ABSTRACT

The production procedure for curved hull plates follows a sequence of shell development, plate cutting, roller press bending, and line heating processes. The final accuracy of shell plates to be formed depends on eliminating errors accumulated during each process. To satisfy shipyard demand for improved accuracy, each process requires careful examination and the entire system should be concurrently integrated. However, previous research and development has been limited to each independent process.

An integrated approach for a computerized production process is being developed. This paper presents the basic concept of the approach. The approach is developed based on engineering analysis in order to guarantee the desired accuracy. Thus, it includes mechanical simulation of cutting, roller press bending, and line heating, with kinematics of shell development. Practical experiences of shipyard experts are implemented into the proposed system by means of a knowledge-based neural network system. Numerical examples are provided to illustrate the present approach.

NOMENCLATURE

A/C	Accuracy Control
ANN	Artificial Neural Network
CAD	Computer Aided Design
CAL	Computer Aided Lofting
CIM	Computer Integrated Manufacturing
DB	Database
FEA	Finite Element Analysis
N/C	Numerically Controlled
OLP	Off-Line Programming

INTRODUCTION

A ship's hull consists of various three-dimensionally curved plates. In particular, highly complex curved plates exist at both the bow and the stern. The production procedure for curved plates follows a sequence of hull modeling, lofting, cutting, roller bending, and line heating.

Hull modeling and lofting are approximate in nature, and are manually carried out by experienced loftsmen or by using commercial computer aided lofting(CAL) systems. The historical background and recent CAL systems, especially for shell development, can be found in a paper by Lamb[2].

The first stage of hull piece production involves cutting, and the quality of cut pieces affect the subsequent production process. Numerically controlled(N/C) cutting is widely used at many shipyards, and the control of precision in the cutting process is a recent production issue in shipyards. Nonetheless, only limited studies have been conducted to investigate the cutting mechanism. Only limited data, such as torch speed, gas pressure, and plate thickness, are available from vendors. Skilled workers can adjust machine parameters in order to cut plates accurately, based on their experience. To improve cutting quality and to reduce residual deformations, cutting sequences, mechanisms to fix plates, and effective cooling methods require clarification.

The formation of compound-curved shells from developed flat plates is the reverse process of shell development. Automation of the plate forming process has made little progress due to difficulties in theoretical and quantitative analyses of the forming mechanism. Consequently, the plate compounding process depends mostly on the personal experience of technicians, which cannot be organized into a reliable technical database.

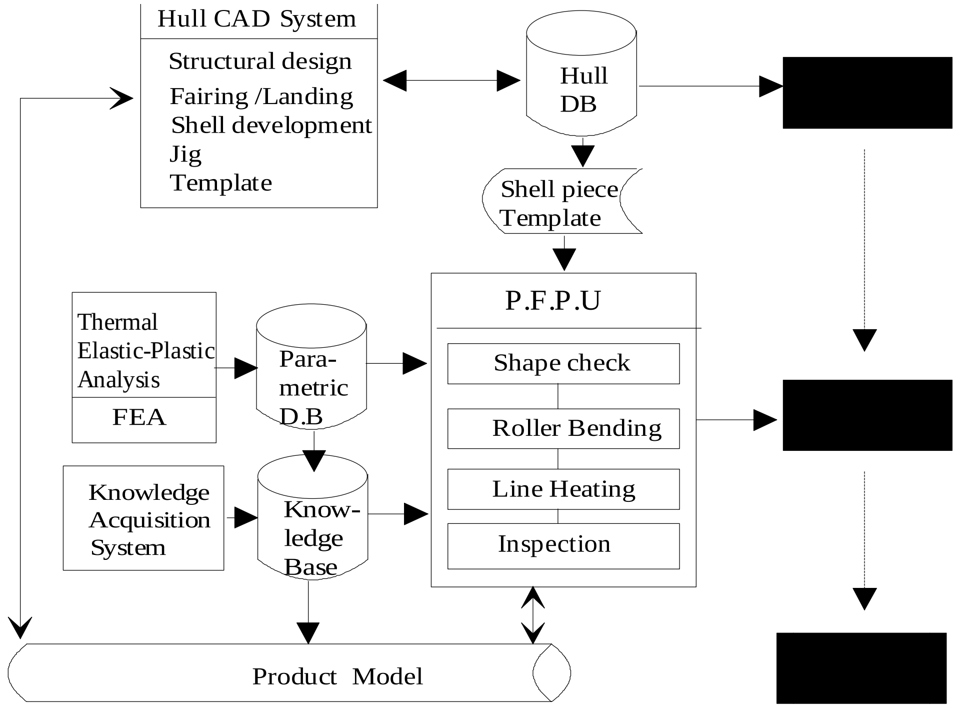


Figure 1 System configuration of plate forming

From current shipyards' practices for the production of curved hull plates, two fundamental limitations can be observed. First, each process is carried out based on individual experience, especially for roller bending and line heating. Secondly, each process is isolated from the others. That is, only the information on externally measurable shape is available at each shop. However, internal state variables, such as residual stresses and strains, are important for the formation of curved shells.

In order to improve the productivity, an automated procedure is preferrable. Automation can only be feasible when both theoretical analyses of the production process and the experiences of experts for each process are available. Therefore, mechanical models of curved hull manufacturing, such as cutting and compounding, are a milestone on the way to a computerized mechanization or automation system.

Also, to achieve truly effective computerization of the production process of curved hull plates, it is necessary to maintain an integrated approach at lofting and manufacturing stage, such as hull landing, shell developing, cutting and forming, compared to that required for the system depending on isolated automation.

An integrated system is being developed for the production process of curved plates. This paper presents the basic concept for the approach. It is based on recognizing that the entire system cannot be successful without success in each individual process. The production process of curved plates is classified into hull lofting, cutting, and forming. For purposes of this paper, the characteristics of each process are discussed from the standpoint of computerization. Mechanics-based simulation with the finite element analysis(FEA) is performed in the process and data flow between processes is studied. A neural network concept is employed for effective integration of data analyses and expert knowledge.

This paper does not present the detailed descriptions of analyses of each forming process. These will be treated in separate papers. This paper introduces mechanisms of each process and focuses on how to integrate each process of lofting, cutting, roller bending, and line heating in order to make the production system complete.

PROPOSED CONFIGURATION OF PRODUCTION SYSTEM FOR PLATE FORMING

Since integrated information supplied for and collected from each process of hull modeling, lofting, cutting, and compounding, is crucial for effective performance of the hull plate production procedure, a computerized system for the complete production procedure is proposed. The system configuration for plate forming of a ship's hull is conceptually illustrated in Figure 1.

Hull geometric information is the basis for the process. This information can be transferred directly from computer aided design(CAD) data at the design stage and translated to production data at the lofting stage. Computerization of mold loft work, such as lines fairing, landing, shell development, jig setting, and template making has greatly advanced in recent years with progress in computer technology. The lofting process produces N/C data, templates, and other information formats. Thus, the processes should include essential accuracy control(A/C) requirements.

N/C cutting is widely used at many shipyards, but it is generally thought that performance accuracy could be greatly enhanced. Deformation and shrinkage allowances should be specified differently according to plate thickness, cutting contour, bevel shapes, and so on. Kerf tolerances, accuracy check, and more complete care for the N/C machine should be

performed regularly and frequently.

The plate forming process unit(PFPU) in Figure 1 consists of an initial shape check, roller bending, line heating, and a final shape check.

The process of manufacturing double-curvature plates is so complicated that not only geometrical calculations, but also work experience, must be taken into account. Feedback of accumulated data from shops is essential for effective application to the next generation of sister ships. An artificial neural network(ANN) algorithm is adopted here to produce production data in time. Finally, a practical system should integrate all the forming processes with computer aided design and manufacturing in order to make the entire process ‘concurrent.’

A detailed description will be followed for each process.

Hull Modeling and Lofting

The first activity in hull construction is modeling and lofting of a hull surface. It is important that the model of a hull surface is created in sufficient detail so that all subsequent lofting operations, such as seams, longitudinal landing, shell plate development, templates, and jigs can be carried out with accuracy. Usually, from the hull surface model, seams, butts, and traces for both longitudinals and transverse frames are decided first, followed by information on shell development, templates, and jigs. The production information and manufacturing documents required for plate forming can be created manually or by using commercial CAL systems such as NUPAS, TRIBON, AUTOKON, and FORAN.

In the modeling of a ship’s hull, hull fairing is performed to refine the shape quality in terms of certain criteria for surface fairness or smoothness while conserving significant characteristics of the shape, since a ship’s hull possesses an aesthetic aspect and, thus, consists of many types of curvatures. A sample drawing from a ship’s hull surface model is shown in Figure 2.

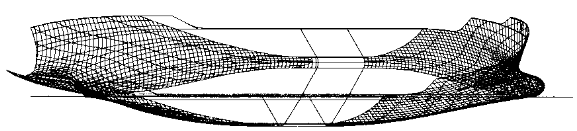


Figure 2 Hull modeling using wire-frame and cross fairing

Surface curves may be referenced so as to define seams and butts for plating arrangement. Longitudinals and seams-and-butts are to be organized by the most suitable hull surface coordinate based on the offset data such as frame lines, water lines, buttock lines, and auxiliary curves. This process, referred to as landing, should bring accurate results to the calculation of shell development, rolling lines for press bending, templates for curved plate, jig tables, and final marking plans for the next assembly stage. A sample drawing of the landing information for a body plan is shown in Figure 3.

Double-curvature shells are geometrically non-developable and, thus, cannot be developed exactly, although many types of developing methods have been presented. Thus, they always deviate from the intended sculptured surface, due to unavoidable approximation in the development technique. The developing method must, in some way, be dependent on the plate forming process, which may be regarded as the inverse function of a development technique. The development technique takes the amount of stretching or shrinking at the line heating process into consideration [3]. A sample drawing from a hull model to prepare shell development data is shown in Figure 4.

Due to inevitable errors in shell development and in the analysis of forming mechanisms, marginal material remains around the edges which must be

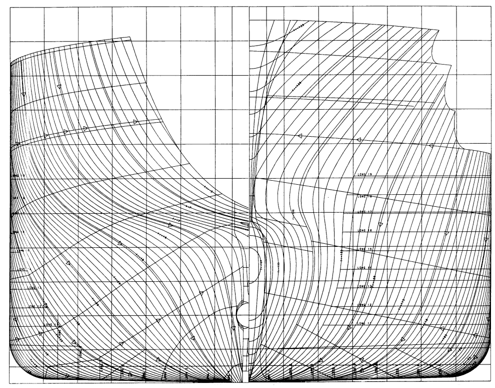


Figure 3 Landing of a body plan

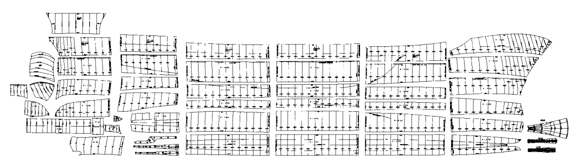


Figure 4 Shell development pieces

trimmed off during the assembly process. ‘No margin’ is every shipyard’s desire, but, thus far, this has not been achieved. With marginal material, the productivity of block construction is difficult to improve, and, in an extreme condition, product quality might deteriorate. Therefore, in preparation of manufacturing data for plate forming, an optimal procedure should be employed in searching for a shell development routine which requires the least manufacturing cost. The relation between developing and forming methods should take this aspect into consideration.

For checking or inspecting a manufactured shell plate, it is necessary to make corresponding templates which will be placed to the shell plate surface. The information on templates is calculated for each plate piece in a CAL system. Work instructions prepared during lofting determine the effective performance of plate-compounding workers. Marking lines, sight baselines, and roll lines for press bending are determined and included in the work instructions. Each template has a sight line mark. The sight baseline serves to fit each template at a prescribed position with a specified angle relative to the plate

surface. When a shell plate is formed correctly, the sight line marks of all templates for the surface are aligned. A typical template drawing for a convex type shell plate is shown in Figure 5 where height is given at each template position.

The lofting work, including templates and jigs, should be automated and computerized in the plate forming system as proposed in Figure 1. Electrical templates with auto-sensing devices and motor-driven pin jigs are preferable for this system.

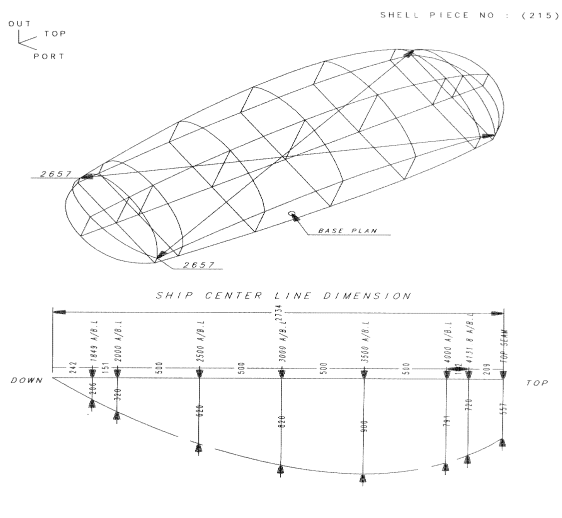


Figure 5 Bending templates for a shell plate

Cutting

When the shell development is finished, the cutting plan of each piece is drawn by adding cut-out tolerance to the shell development.

The cutting process, the first stage of the hull piece production, is very important, since it should produce the exact shape of the desired flat plates with minimal residual deformations and stresses. The improvement of precision in the cutting process is one of the recent production issues in shipyards. Here, three issues can be clarified in the cutting process regardless of heat sources:

1) Methodology for cutting the exact developed surface,
2) Methodology for reducing residual stress, and
3) The size of the cut-out width.

N/C cutting is widely used at most large shipyards. The N/C process is connected to the shell lofting data via a network or removable diskettes. The progress in computer-aided hull construction technology and the wide application of new N/C cutting machines at shipyards in the past two decades help improve the accuracy of the cutting process. Though the cutting process data are supplied by machine vendors, the cutting expert's intuition and experience play an important role in successful cutting jobs. There are many factors which affect the accuracy of cut plates

However, studies investigating the cutting mechanism are few in number. To minimize cutting errors and residual deformations, cutting sequences, mechanisms to fix plates, and effective cooling methods require further study. For this, a mechanics-based approach to the cutting process is recommended. Shrinkage allowances should be specified differently for different parts, such as the parallel edge part, internal part, etc. Kerf tolerances should also be specified.

In the proposed system, a computational method is developed to simulate the cutting process based on thermal-elastic-plastic stress analysis. The cutting process is a non-linear as well as a non-steady state problem. Many parameters, which are expected to produce errors, are coupled. It is therefore impossible to analyze the influence of each parameter by experiment. Therefore a computer simulation method which is based on mechanical theory is one of the most effective approaches. FEA is a useful tool for this type of complex problem. The two-dimensional and three-dimensional temperature fields are calculated, based on the modeling of heating. When the temperature of an element reaches the melting point, the element is cut off in the analysis. The simulation modeling in Figure 6 shows that a plate is cut by a moving torch.

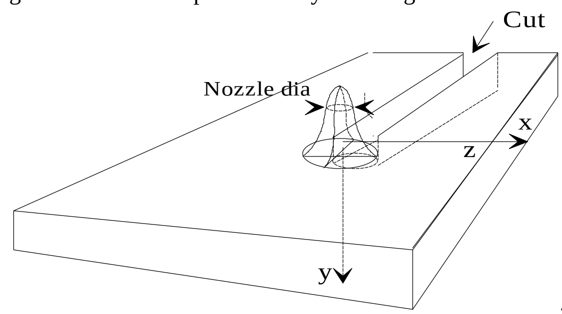


Figure 6 Cutting process modeling

Residual deformation, groove shape, and stress are also investigated. Figure 7 shows an example of the kerf shape during the process.

There are several parameters which govern the quality of cutting. Among them are plate thickness, shape, materials, torch speed, and gas pressure. Parametric studies are performed to determine the effect of input quantities for the cutting. These simulated cutting results can be used to improve the cutting accuracy and the forming process.

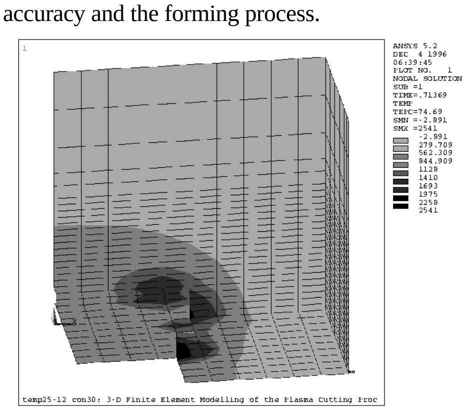


Figure 7 Kerf shape by FEA

Forming

Overview of the forming process

Cut pieces, templates, and forming plans of curved plates are provided to the forming shop. In a forming plan drawing, an offset table and roll lines are shown. No other production information is available. Even with such insufficient data, an expert in the forming shop sketches the shape of a curved shell and determines the amount of curvatures qualitatively. A shell is grouped into one of typical forming processes; convex, saddle, and twisted types. The process is solely dependent on experts' intuition and experiences. The process is completed when the formed shell fits to the pre-manufactured templates.

Formation is a process of applying some degree of permanent strains to flat plates using mechanical and/or thermal tools. A single-curvature shell can be easily formed from a flat plate because it requires only bending or rolling of the plate. In case of the formation of double-curvature shells, primary bending is usually performed by a press or a roller, followed by line heating. Other methods, such as dieless forming and induction heating are used at some shipyards as well.

At the moment, none of the forming methods has yet been fully automated nor computerized. There are accuracy problems in the forming process, since the underlying mechanisms of any forming process are not fully understood and, thus, the forming is done on an empirical basis regardless of forming methods.

In this proposed system, the forming process of press bending and line heating is analyzed numerically and the results are incorporated into the system. The production information on rolling and heating parameters are quantified as much as possible for automation and computerization of the process.

Geometry and Kinematics Information

Formation or compounding is a process of applying permanent strains to a blank plate. Therefore, the geometric relation, or kinematics, between a shell plate and the flat plate forms the basis for the computerized production process with mechanization or automation. Curvatures, in-plane strains, and bending strains represent the three major parameters for the forming process.

Those kinematic quantities, i.e. curvatures and strains, are calculated, based on differential geometry theory, by mapping a curved shell with a blank plate. With given offset data for the shell plate to be fabricated, curvatures can be calculated directly. For practical purposes, the formulation is made to use the offset tables provided with a blank plate [9]. The calculated curvatures and strains are key parameters for the determination of rolling lines, rolling width, pressure for roller bending, as well as heating path, torch speed and power for line heating.

In the proposed system, the curvature of a shell is first calculated for each piece of steel plate. The obtained curvature will aid workers in understanding the types of the plate pieces. In-plane and bending strains are then determined between the shell plate and the blank plate. After roller bending is applied, it is useful to understand the remaining strains that contribute to the final shape. Thus, those strains are also calculated between the final shape and the single curvature shell fabricated by a roller press.

Real examples from shipyard's data are provided for applicability of the present approach. Figure 8 shows the cubic B-spline modeling, bending and inplane strains for the corresponding undevelopable surfaces.

When the accurate mapping between the developed plate and the desired hull surface is obtained, the optimal rolling lines and heating paths can be determined, which, in turn, contribute to the reduction of the forming energy and the prevention of change in material properties, due to the excessive heat supply.

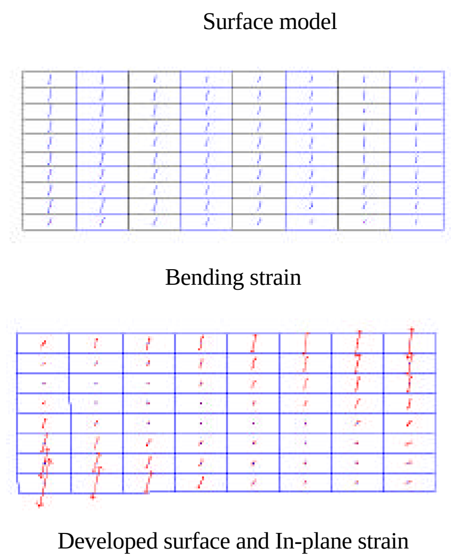


Figure 8 Kinematic information of a hull surface piece

Roller Bending

Roller bending is a process of forming single curved shells. A single curvature shell may be a final shape to be formed itself or, alternately, an intermediate shape for a double curvature shell. However, for a double curvature shell, the amount of curvature by roller bending is dependent on the line heating processes that follow.

There are various types of roller bending machines including pyramid- and pinch-type. The pyramid-type three roll bending machine, shown in Figure 9, is widely used in shipyards. It consists of three rollers, one center roller which can move only vertically and two fixed side rollers. Control of the vertical displacement of the center roller and the horizontal movement of a blank plate determines the shape and accuracy of single curvature shells. This job is done by workers in a trial-and-error manner.

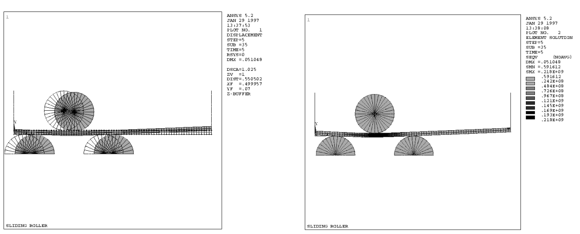
In this integrated approach, the pyramid-type three roll bending machine considered. Figure 9 shows the configuration of plate bending procedure by the pyramid type three roll bending machine. First, a workpiece is inserted between center roller and two side rollers and is bent by imposing vertical

displacement of the center roller. Then, the plate is bent sequentially by rotating three rollers simultaneously.

For automation and computerization of the process, the relation between the vertical movement of the center roller and desired curvature requires clarification [1]. First, the elasto-plastic bending phenomenon is analyzed using the beam theory. Both one-time bending and sequential bending are calculated. The vertical displacement of the center roller is obtained to give constant curvature to the plate. Also, the curvature distribution along the arc length is constant when the vertical center roller displacement is constant. Then, FEA is employed to obtain and compare the results with those by the beam theory.

In the FEA, the workpiece is modeled using beam and plane strain elements. Figure 10 shows the finite element model and stress distribution of the roller bending process midway in sequential bending. The
results show good agreement with those of the beam theory.

When the single curvature shell is formed as an final intermediate shape, the effect of the roller bending to the compound-curved shell must be addressed. The supplementary strain is calculated after the roller bending is finished.



(a) Deformed shape (b) Equivalent strain distribution

Figure 10 Configuration of roller bending procedure.

Numerical calculations
are made with actual production data used in a shipyard. Figure 11 shows the first bent surface and the distribution of the insufficient bending strain between the desired saddle surface and the first bent shape. The supplementary bending strain is 60% of the initially required one.

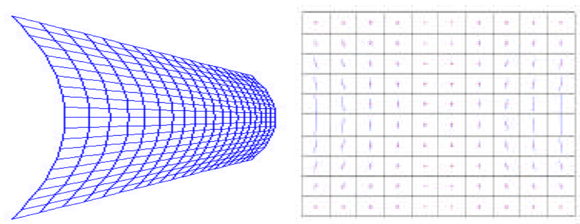


Figure 11 Rolled shape and bending strain distribution of the saddle type

<u>Line Heating</u>

Line heating is used to form double curvature shells from single curvature shells by controlled heating and cooling. However, most of the studies have been performed for flat plates.

In the proposed system, a numerical approach to three-dimensional temperature and strain analysis is employed [8]. For a formed single curvature shell, FEA is applied by using solid elements. An example of a calculation model and a finite element modeling is shown in Figure 12.

In the FEA, temperature and strain fields are uncoupled. For temperature analysis, heating torches and cooling hoses are modeled as heat flux and convection condition, respectively. The calculated temperature field is used as a loading condition which creates residual deformations in the shell. Factors, which affect the result of line heating,

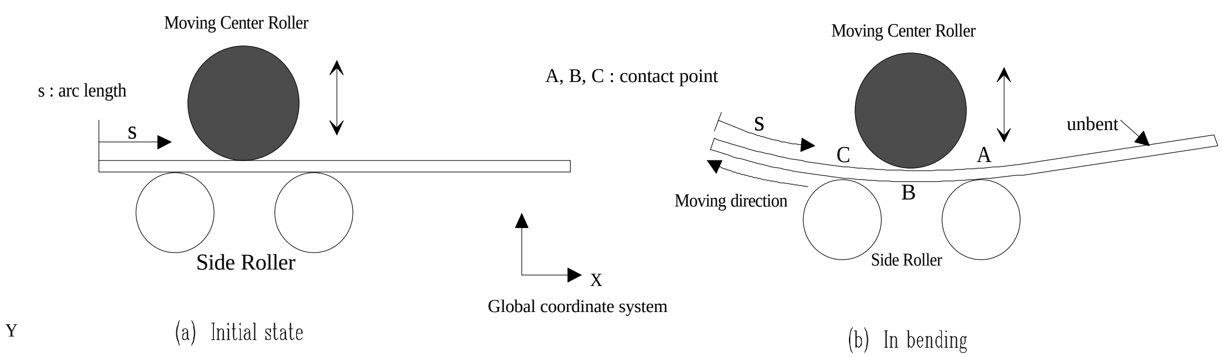


Figure 9 Configuration of roller bending procedure

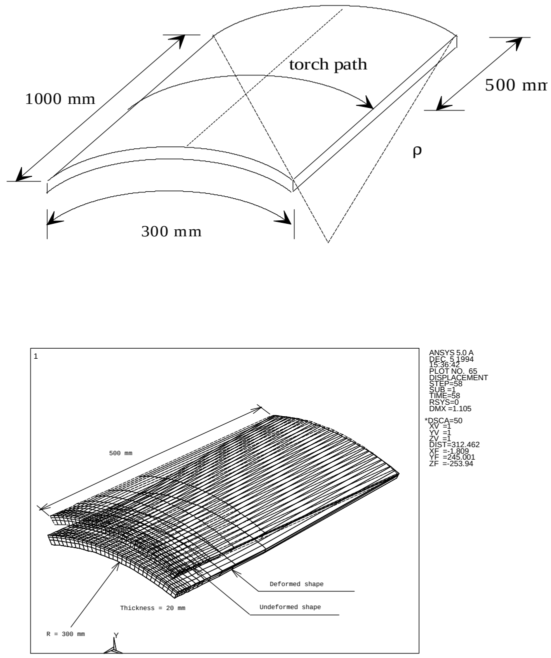


Figure 12 Finite element modeling and deformed shape of the initially curved shell

include the type of heating source, torch temperature, torch speed, material properties of plate, plate thickness, geometry, initial curvature, and cooling method. A parametric study is performed to determine the effect of each parameter. An example of deformed double curvature shell by FEA is shown in Figure 13.

FEA is useful, since each factor which affects the final deformation can be easily examined. However, the computing time is still enormous and, as a result, FEA is not practical for the automation or computerization of line heating. An Off-Line Programming(OLP) approach, recently employed in welding processes, is recommended for the proposed system. Relevant

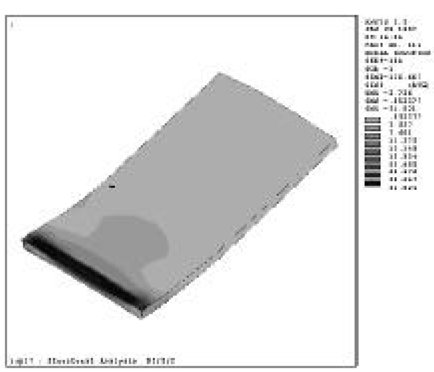


Figure 13 Simulation of line heating process for the initially curved shell

information is calculated and stored in the database prior to the application of line heating. Since the stored data are not always obtained from the same shape to be formed, a data converting process is included. An ANN approach is adopted for this system as described next.

Application of Artificial Neural Network to a Knowledge Based System

In plate production, especially in line heating, the years of accumulated knowledge is personally used by the worker, which results in a considerable waste of time in the training of new workers and computerizing the process. Therefore, one purpose in developing a knowledge-based system is that the user makes the best use of the accumulated skills of prior experts by sharing the accumulated knowledge. The skill must be represented as knowledge, and the knowledge must be stored in the computer in the form of expressions. The constructed knowledge base is then sufficiently flexible and can be used for modification, maintenance, and extension of concepts.

To develop a knowledge-based system for hull plate production, we adopt the ANN approach for the practical use of numerical analysis information. The information should systematically be analyzed so that it can be applied to a knowledge-based system.

The ANN technique deduces certain parameters from a database. In the proposed system, the database contains forming information from the numerical simulation of line heating. The use of ANN reduces the amount of computer time required to solve iterative analyses of the line heating problem for formed plates. The back-propagation model is adopted in the network. Also, the ANN can be applied to the construction of the database.

Here, for the understanding of the system, the basic concept of ANN will be briefly discussed[9]. ANN has a multi-layer network structure. Arranging neurons in layers resembles the layered structure of a certain portion of the human brain. Back-propagation networks have such structures. The output values are obtained by multiplying input values by weights. Each neuron in subsequent layers produces output values as described above. A network is trained so that the application of a set of input values produces the desired set of output values. Training is accomplished by sequentially applying inputs, while adjusting network weights according to the predetermined procedure. During training, the network weights gradually converge to values such that each input produces the desired output.

ANN with back-propagation requires the pairing of each input value with the target value representing the desired output. These are collectively referred to as a training pair. The network is then usually trained over a number of such training pairs. When an input vector is applied, the output is compared to the corresponding target value, and the difference is fed back through the network during which weights are changed to minimize the error. The values of a training set are applied sequentially. Errors are calculated and weights are adjusted for each value until the error for the entire training set is at an acceptably low level. If there are a sufficient number of training pairs, the neural network will give exact output. There must, therefore, be sufficient results from numerical analysis or real

data.

If training pairs are made among these ingredients, plate thickness, size of plate, and initial curvature of plate can be used as inputs, and targets can be comprised of torch speed and the location of the heating line.

In an example of the ANN, factors that affect the final deformation by the line heating are considered. Then, the training pairs are made from plate thickness, torch speed, and initial curvature as input and from maximum vertical displacement as output. To verify the validity of the neural network, the results by the ANN with data from the three-dimensional analysis of line heating by FEA are compared, as shown in Table I and II.

By varying the number of hidden layers and the number of neurons in each hidden layer, it is concluded that if the number of neurons in each hidden layer is sufficiently large, a neural network having two hidden layers can be easily trained and errors between the exact value and that from the trained network are acceptable.

Consequently, if there are a sufficient number of training pairs, the artificial neural network in the proposed system can infer similar results. With the numerical results, the artificial neural network technique is applied to economically determine the forming parameters.

CONCLUSIONS

Due to personnel problems in the shipbuilding environment which arise from social evasion from

Curvature (ρ : mm)	thickness (t : mm)	torch speed (s :mm/sec)	max. Deflection (δ : mm)
1000	20	7.5	3.654
1000	20	10	2.413
1000	20	12	1.917
1000	25	10	1.958
1000	25	12	1.71
2000	20	7.5	3.328
2000	20	10	2.465
2000	20	12	2.04
2000	25	7.5	2.169
2000	25	10	1.981
3000	20	7.5	3.219
3000	20	10	2.471

Table I Training pair

ρ	t	s	δ (exact)	δ (1)	δ (2)
1000	25	7.5	2.406	2.56 (+6.4%)	2.868 (+19.2%)
2000	25	11	1.89	1.8963 (+0.33%)	1. 838 (-2.75%)

(1) Network with two hidden layers. Four neurons for each hidden neurons(Training number = 162900.)
(2) Network with two hidden layers. Six neurons for each hidden layers. (Training number = 227700.)

Table II Result from training pair

difficult, dirty, and dangerous jobs, labor-management conflicts, and the high cost of labor, a gradually decreasing number of skilled technicians and, hence, increased labor costs can be anticipated. Therefore, the automation and computerization of the hull construction process is required. Current practices in compounding hull plates are dependent on individual experience and each process is isolated from the point of view of information flow. This, in turn, reduces productivity and prevents the development of automation.

In this paper, a conceptual configuration and related processes for CIM are proposed for the formation of ship's hull plates. It is necessary to integrate lofting, cutting, and plate forming activities for A/C and minimum energy in the compounding process.

The proposed system is established after shell development, cutting, roller bending, and line heating processes are analyzed analytically and/or numerically. For effective forming process, the importance of physical quantities, such as curvatures and strains is discussed. Some examples of numerical calculations are introduced in each process to explain current practices and future development of the integrated system.

To improve productivity through automation, analysis results of each forming mechanism and experts' knowledge must be integrated. The numerical results are incorporated into a knowledge-based system by application of ANN with back-propagation algorithms. The system is constructed to be compatible with current CAL systems and aids workers in the determination of forming parameters at each stage, since it follows the ongoing forming process.

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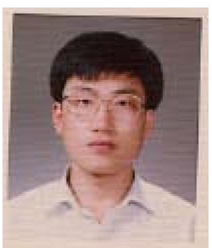

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Use Of Variation Merging Equations To Aid Implementation Of Accuracy Control

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ABSTRACT

Implementation of accuracy control in U. S. shipyards has encountered a number of impediments. These include the short run nature of shipbuilding, the difficulty in understanding the specifics of data collection, and the difficulty in prioritizing data collection efforts. As a part of it s return to new construction, with the building of three new Jumbo Mark II Ferries for the State of Washington, Todd Pacific Shipyards was hoping to implement accuracy control. This paper reports on a new approach to the use of variation merging equations as a means of prioritizing data collection efforts. The research, performed by University of Washington researchers in conjunction with Todd personnel, was successful in helping prioritize efforts to improve implementation of accuracy control.

INTRODUCTION

A recent study comparing U.S. shipbuilding practice to best international practice identifies a number of major areas of deficiency. Included in these is the application of the principles of Total Quality Management (TQM) [1]. A part of TQM applied to production involves the capability to efficiently control accuracy of interim products at each stage of construction. The goal of the research reported in this paper is to aid implementation of an accuracy control system that will enable a shipyard to control accuracy of interim products at each stage of construction, so that the amount of rework at the erection stage is decreased. Furthermore, the methodology developed in this research will enable the shipyard to predict the probability of rework at erection, which will in turn be beneficial to production planning and scheduling. Thus, the aim of this research is to assist in the development and implementation of a short run Statistical Process Control (SPC) system at a shipyard.

In order to fulfill the goal of this research, a construction project for the initiation of the system is required. That opportunity is provided by the Washington State Ferries (WSF) construction program awarded to Todd. The program initially involves the construction of three new Jumbo Mark II Ferries.

BASIC CONCEPT

A mature accuracy control system maintains and uses a substantial data base. Often, shipyards faced with implementation of a new accuracy control system, have difficulty in facing the enormous data collection and analysis effort required. Short term goals tend to preclude the completion of the time consuming data collection process. Thus, the long term needs of an accuracy control system are not satisfied.

An alternative to performing the data collection effort as a major undertaking is therefore employed. Shipyards prioritize processes for beginning data collection, with the goal being to incrementally develop the full data base required. Here again, many shipyards lose the will to complete this effort, and never fully achieve an accuracy control system. A key decision in any incremental approach to data base development is how to prioritize processes for initial data collection efforts. The common approach has been to employ the advice of consultants, or use in-house experience to make this choice.

The goal of this research is to test an alternative concept. The approach is to write variation merging equations using symbols for all variations, and use these equations to identify critical points and dimensions, as well as critical processes. Based on this, accuracy control planners have a better understanding of the priorities for data collection. Figure 1 shows this new concept.

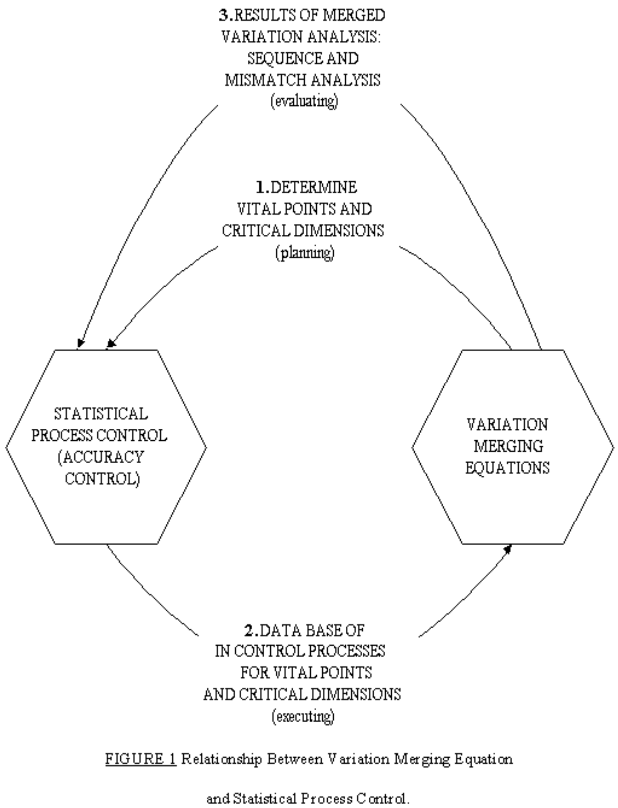


Figure 1 Relationship of Variation Merging Equations and the Accuracy Control System

STRUCTURAL SECTION

In order to test the concept of using variation merging equations to aid the development and implementation of a short run Statistical Process Control (SPC) system, or an accuracy control system, a project and specific structural section are chosen. The construction of three new ferries for the State of Washington provides the project on which to begin implementation of this short run SPC system. To simplify program implementation, concentration is only on structural work, omitting the outfitting work.

Figure 2 shows an outboard profile of the Jumbo Mark II ferry, detailing the block (unit) breakdown. Unit 107, an engine room unit, is taken as the starting point for developing the variation merging equations (see Figure 3). In spite of the difficulties in developing the variation merging equations for such a complex unit as unit 107, the benefits emerge during the generalization of the variation merging equations. Even though the variation merging equations are developed only for unit 107, it is an adequate example for establishing the guidelines for determining the vital points and critical dimensions, as well as critical processes at each stage. Furthermore, as will be pointed out later, the adaptation of the variation merging equations for other units requires little effort, compared to the effort required for developing the first series of variation merging equations.

This variation merging analysis provides the framework for the analysis of hull merged variations at the block (unit) assembly stage of construction. Once the data becomes available, results of this analysis can be used directly to perform assembly sequencing analysis, and mismatch analysis.

SHORT RUN STATISTICAL PROCESS CONTROL

Historically, control charting is applied in manufacturing where a large number of identical parts are being produced. With the general trend toward product customization, batch sizes are significantly reduced, sometimes even to one. Furthermore, Just-in-Time (JIT) manufacturing also causes a need for decreasing batch size, because this pull system means that the amount of production is driven by the immediate need for final assembly [2]. Consequently, the short run control chart was developed and is in common use for these situations.

Applying the principal of $\overline{X} - R$ control charts to short run production, the measured quality characteristic is replaced by deviation from nominal. This can be expressed in the form of the following equation:

$$x_{i,w} = M_{i,w} - N_w \ , \qquad (1)$$

where

$M_{i,w} =$ the i th actual sample measurement of the quality characteristic of w,
$N_w =$ the nominal value of the quality characteristic of w, and
$x_{i,w} =$ the deviation of the actual measurement from nominal of the i th sample of the quality characteristic w.

Then, the principal of standard $\overline{X} - R$ control charts is utilized. [3]

Furthermore, in the case where the measurement sample size is one, the ideas of short run process control can be combined with the principal of $\overline{X} - MR$ control charts, resulting in the short run $\overline{X} - MR$ control chart. This was used to sample and analyze data from a

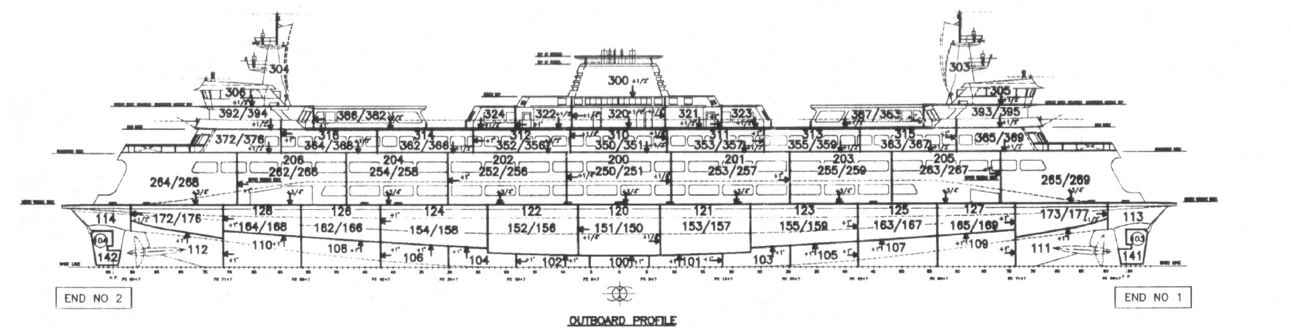


Figure 2 Outboard Profile of Jumbo Mark II Ferry Showing Block Breakdown

numerical control (N/C) cutting machine. Figure 4 shows the application of the short run $\overline{X} - MR$ control chart to the N/C cutting process (the data were acquired by accuracy control personnel at the shipyard).

DEVELOPING THE VARIATION MERGING EQUATIONS

At any stage of construction, variations can be classified into two types, the variations associated with the input components, and the variations introduced by the joining process. Thus, the basic information necessary to develop the variation merging equations for unit 107 includes:

- structural geometry of unit 107,
- structural geometry of the components of unit 107, and
- assembly procedures used in fabricating unit 107.

The assembly sequence actually employed for unit 107 results in inconsistencies in the merged variations to the interim products at the unit assembly level. For this reason, a specific and repeatable assembly sequence is used in the development of the variation merging equations. The details of the new assembly sequence are discussed in the next section.

Figure 3 is a sketch of the half-breath or cross sectional view of unit 107. The design of unit 107, as well as other units in this ferry, prevents significant merged variation in the longitudinal direction, by having very few longitudinal joints. The same is not the case in the transverse direction. The merged variations in the transverse direction are far more significant than those in the longitudinal direction. This situation is confirmed by the accuracy control personnel at the shipyard. As a result, the variation merging equations are developed in the transverse direction, instead of the longitudinal direction, as is the more conventional application of variation merging equations. This is also evident when considering that the scope of this work is focused on merged variations at unit assembly.

Assumptions Used In Variation Merging Equations

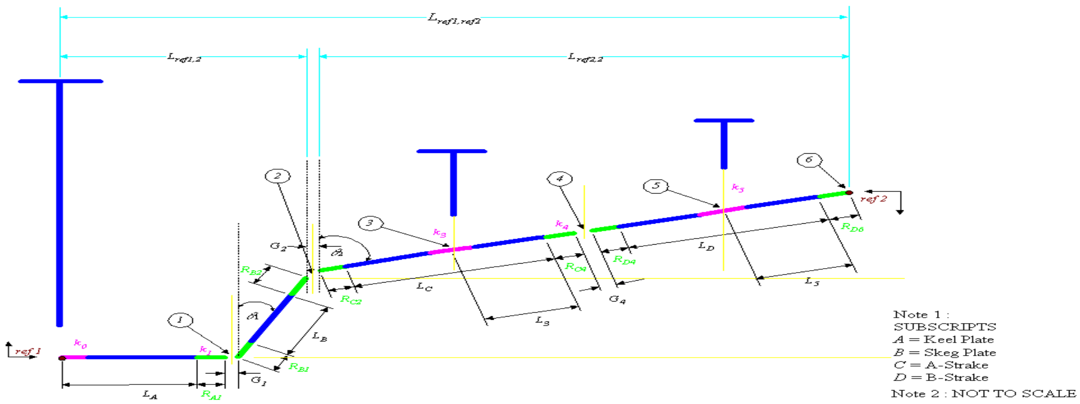
A uniform assembly sequence for unit 107 is chosen and is shown in Figure 5. As is shown in Figure 3, unit 107 is divided into two sub-units. Sub-unit 1 contains plates A and B, and sub-unit 2 contains plates C and D. Sub-unit 1 is assembled on the flat ground and then loaded onto a pin jig during the unit assembly stage. Sub-unit 1 is set on the pin jig with reference to *ref 1*. Sub-unit 2 is assembled on the pin jig with reference to *ref 2* (see Figures 3 and 5). Finally, both sub-units are joined at weld joint #2.

Apart from the general assumptions of rectangularity and flatness that must be made, an additional assumption is needed to facilitate the development of the variation merging equations. This additional assumption is that weld shrinkage is equally distributed about the weld seam. The logic of this assumption is based on the fact that both components are made from the equal thickness plates.

It is only at weld joint #1, between the keel plate and the skeg plate, or plate A and plate B in Figure 3, that the thickness between the two plates is different. The welding shrinkage is assumed to be directly dependent on the thickness of the plate, or $\text{Shrinkage} \propto (\text{Thickness})^{-1}$.

Variables In The Variation Merging Equations

Figure 3, a sketch of unit 107, provides the notation used to define the variables used in the



Weld joint

(1) indicates weld joint #1

(2) indicates weld joint #2

(3) indicates weld joint #3 (vertical)

(4) indicates weld joint #4

(5) indicates weld joint #5 (vertical)

(6) indicates weld joint #6 (Block weld joint)

Vital distance

$\mathbf{L}_{11} = \mathbf{L}_{\mathbf{ref}1,1} =$ Distance between reference point #1 (*ref* 1) and weld joint #1

$\mathbf{L}_{12} = \mathbf{L}_{\mathbf{ref}1,2} =$ Distance between reference point #1 (*ref* 1) and weld joint #2

$\mathbf{L}_{13} = \mathbf{L}_{\mathbf{ref}1,3} =$ Distance between reference point #2 (*ref* 1) and weld joint #2

$\mathbf{L}_{14} = \mathbf{L}_{\mathbf{ref}1,4} =$ Distance between reference point #2 (*ref* 2) and weld joint #3

$\mathbf{L}_{15} = \mathbf{L}_{\mathbf{ref}1,5} =$ Distance between reference point #2 (*ref* 2) and weld joint #5

Reference line

$\mathbf{R}_{\mathbf{A}1} =$ Distance between plate edge and reference line at end #1 of plate A

$\mathbf{R}_{\mathbf{B}1} =$ Distance between plate edge and reference line at end #1 of plate B

$\mathbf{R}_{\mathbf{B}2} =$ Distance between plate edge and reference line at end #2 of plate B

$\mathbf{R}_{\mathbf{C}2} =$ Distance between plate edge and reference line at end #2 of plate C

$\mathbf{R}_{\mathbf{C}4} =$ Distance between plate edge and reference line at end #4 of plate C

$\mathbf{R}_{\mathbf{D}4} =$ Distance between plate edge and reference line at end #4 of plate D

$\mathbf{R}_{\mathbf{D}6} =$ Distance between plate edge and reference line at end #6 of plate D

Weld gap

$\mathbf{G}_1 =$ Weld gap at point #1

$\mathbf{G}_2 =$ Weld gap at point #2

$\mathbf{G}_4 =$ Weld gap at point #4

Shrinkage

$\mathbf{k}_0 =$ Shrinkage due to CVK fillet weld at *ref* 1

$\mathbf{k}_1 =$ Shrinkage due to butt weld at point #1; keel plate & skeg plate joining

$\mathbf{k}_1^{/}$: assume $\text{Shrinkage} \propto (\text{Thickness})^{-1}$

$\mathbf{k}_2 =$ Shrinkage due to butt weld at point #2; skeg plate & A-strake joining

$\mathbf{k}_2^{/} = \frac{\mathbf{k}_2}{2}$: assume equal heat distribution about welding point

$\mathbf{k}_3 =$ Shrinkage due to girder fillet weld at point #3; on A-strake

$\mathbf{k}_3^{/} = \frac{\mathbf{k}_3}{2}$: assume equal heat distribution about welding point

$\mathbf{k}_4 =$ Shrinkage due to butt weld at point #2; A-strake & B-strake joining

$\mathbf{k}_5 =$ Shrinkage due to girder fillet weld at point #5; on B-strake

$\mathbf{k}_5^{/} = \frac{\mathbf{k}_5}{2}$: assume equal heat distribution about welding point

Note: Welding shrinkage is a natural negative variable. For example, if the measured shrinkage is 3/16 in., it would appear in the equation as -3/16 in..

Length of plate

$\mathbf{L}_{\mathbf{A}} =$ Length (between reference lines) of plate A

$\mathbf{L}_{\mathbf{B}} =$ Length (between reference lines) of plate B

$\mathbf{L}_{\mathbf{C}} =$ Length (between reference lines) of plate C

$\mathbf{L}_{\mathbf{D}} =$ Length (between reference lines) of plate D

$\mathbf{L}_3 =$ Length between reference line at end #4 and girder at point #3

$\mathbf{L}_5 =$ Length between reference line at end #6 and girder at point #5

Angle

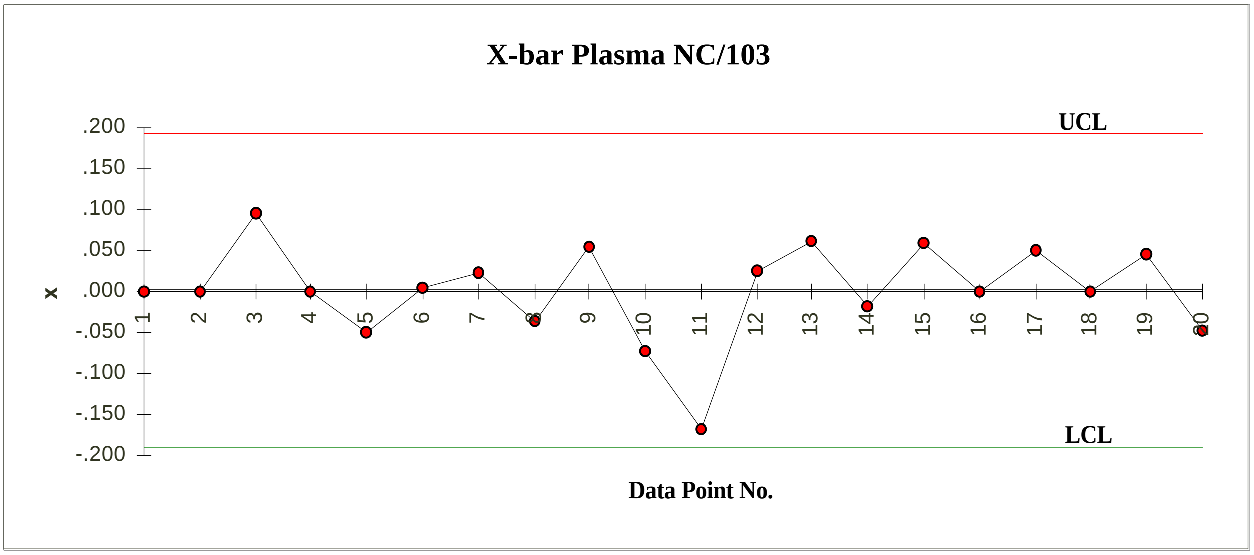
$\boldsymbol{\theta}_1 =$ Angle of plate B reference to vertical plane

$\boldsymbol{\theta}_2 =$ Angle of plate C and D (subassembly C&D) reference to vertical plane

Figure 3 Section View of Unit 107

$\overline{X} - MR$ Control Chart Plot

Hull No. : M7091		Project : WSF	
Unit No. : 103		Date : xx/xx/xx	
Process : Plasma NC Cutting		Stage of Construction : Part Fabrication Stage	
By : John D.		Measurement Description : Cutting dimension from plasma NC machine	
NOTE :	*Sample Size; n = 1*		
	Number of Sample; m = 20		



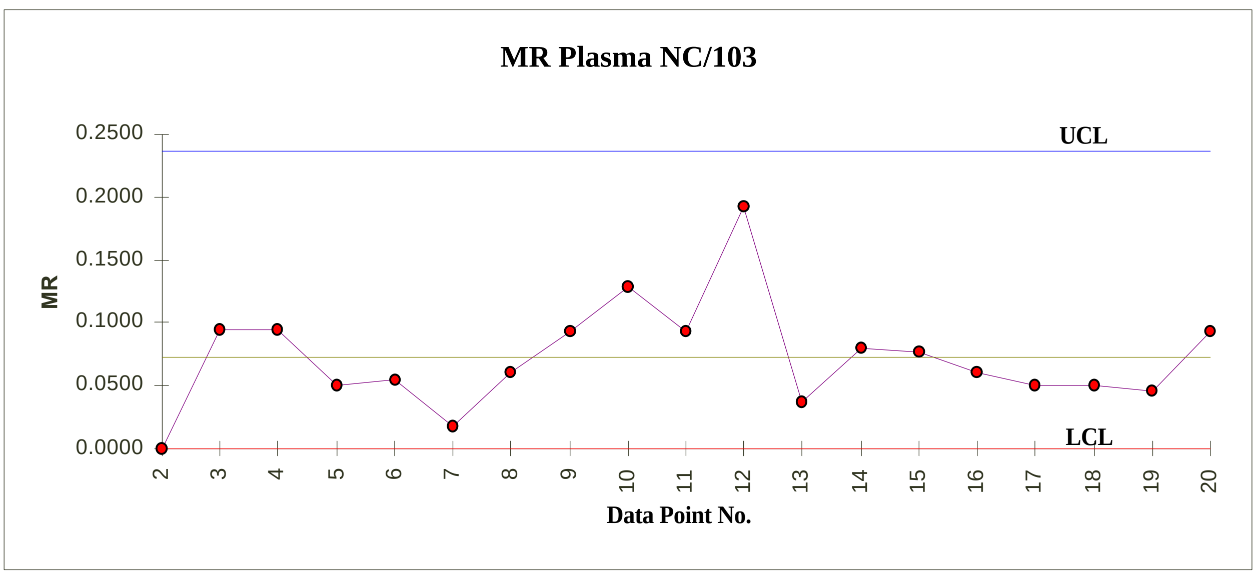


Figure 4 X - MR Control Chart

variation merging equations. The variables refer to both dimensions and measuring methods, as follows.

- L_{nn} denotes the distance from the reference point #*n* to the weld joint #n. The data for this variable is collected at the assembly stage.
- k_n denotes the weld shrinkage at weld seam #*n*. There are 3 types of weld joints: butt weld, angular butt weld, and fillet weld. Each type is subject to different shrinkage amounts. Besides the type of weld, other attributes, including weld gap, type of material, thickness of material, type of edge (i.e., bevel), and welding parameters (heat and voltage) must also be considered.
- L_X and L_n are variables denoting the length between the reference lines. L_X denotes the distance between plate reference lines whereas L_n denotes the distance between the plate reference line and the fillet weld joint reference line. The data for these variables are obtained at the parts fabrication stage.
- R_{Xn} denotes the distance between the reference line and the plate edge at the same end of plate *X*. The data for this variable is also obtained at the parts fabrication stage.
- G_n denotes the width of the weld gap at weld seam #n provided by the fitter. The data for this variable is obtained by measuring the weld gap before welding at the fitting process.
- θ_n denotes the angle of the subassemblies #*n*. The data for this variable is obtained by measuring the elevation and the horizontal dimension of the subassembly, and calculating the inclining angle in reference to the vertical plane. While θ_1 is dependent on the assembly process, θ_2 is determined by the pin jig setting process.

Variation Merging Equations

The variation merging equations developed in this section follow the standard approach, as described in [4]. The equations include the geometric equation, and the variation and variance merging equations. These equations are based on predicting the merged variation at weld joint 2. The resulting geometric equation, variation merging equation and variance merging equation of G_2 are presented as follows.

Geometric Equation:

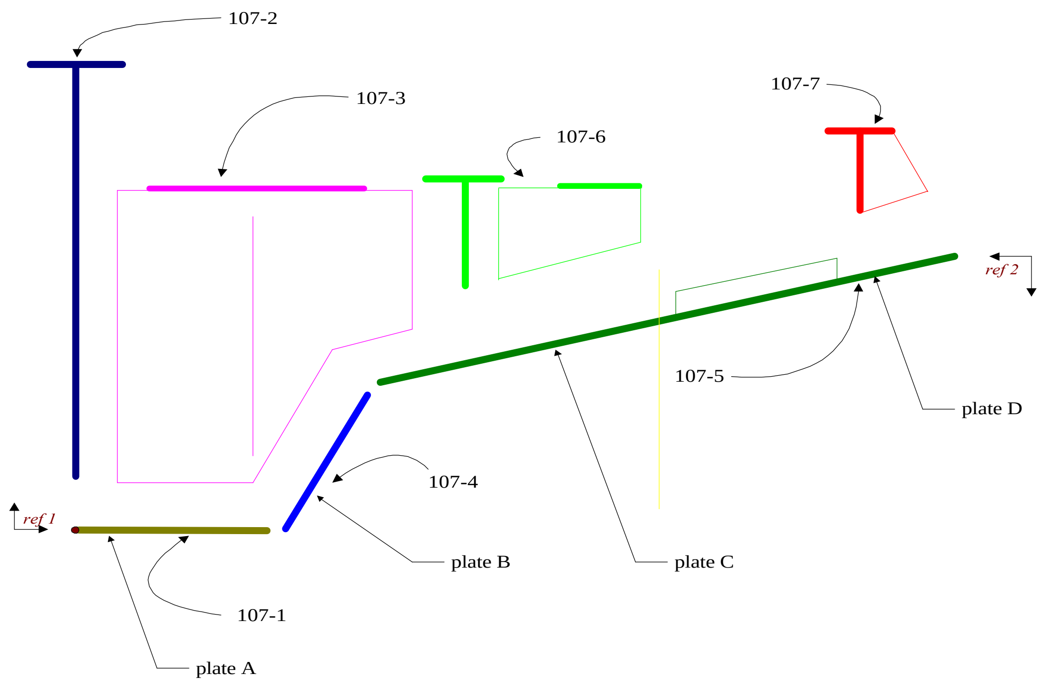
$$G_2 = L_{ref\,1,ref\,2} - (L_{12} + L_{22}) \qquad (2)$$

Variation Equation:

$$\begin{aligned}
\overline{X_{G_2}} = \overline{\delta L_{ref\,1,ref\,2}} - \{[&\overline{\delta k_0} + \overline{\delta L_A} + \overline{\delta R_{A1}} + \overline{\delta k_1} + \overline{\delta G_1} \\
&+ [(R_{B1} + \overline{\delta R_{B1}}) * Sin(\theta_1 + \overline{\delta\theta_1}) - R_{B1} * Sin\theta_1] \\
&+ [(L_B + \overline{\delta L_B}) * Sin(\theta_1 + \overline{\delta\theta_1}) - L_B * Sin\theta_1] \\
&+ [(R_{B2} + \overline{\delta R_{B2}}) * Sin(\theta_1 + \overline{\delta\theta_1}) - R_{B2} * Sin\theta_1] \\
&+ [(k_2^{/} + \overline{\delta k_2^{/}}) * Sin(\theta_1 + \overline{\delta\theta_1}) - k_2^{/} * Sin\theta_1]\} \\
&- \{[(R_{D6} + \overline{\delta R_{D6}}) * Sin(\theta_2 + \overline{\delta\theta_2}) - R_{D6} * Sin\theta_2] \\
&+ [(k_5 + \overline{\delta k_5}) * Sin(\theta_2 + \overline{\delta\theta_2}) - k_5 * Sin\theta_2] \\
&+ [(L_D + \overline{\delta L_D}) * Sin(\theta_2 + \overline{\delta\theta_2}) - L_D * Sin\theta_2] \\
&+ [(R_{D4} + \overline{\delta R_{D4}}) * Sin(\theta_2 + \overline{\delta\theta_2}) - R_{D4} * Sin\theta_2] \\
&+ [(k_4 + \overline{\delta k_4}) * Sin(\theta_2 + \overline{\delta\theta_2}) - k_4 * Sin\theta_2] \\
&+ [(G_4 + \overline{\delta G_4}) * Sin(\theta_2 + \overline{\delta\theta_2}) - G_4 * Sin\theta_2] \\
&+ [(R_{C4} + \overline{\delta R_{C4}}) * Sin(\theta_2 + \overline{\delta\theta_2}) - R_{C4} * Sin\theta_2] \\
&+ [(k_3 + \overline{\delta k_3}) * Sin(\theta_2 + \overline{\delta\theta_2}) - k_3 * Sin\theta_2] \\
&+ [(L_C + \overline{\delta L_C}) * Sin(\theta_2 + \overline{\delta\theta_2}) - L_C * Sin\theta_2] \\
&+ [(R_{C2} + \overline{\delta R_{C2}}) * Sin(\theta_2 + \overline{\delta\theta_2}) - R_{C2} * Sin\theta_2] \\
&+ [(k_2^{/} + \overline{\delta k_2^{/}}) * Sin(\theta_2 + \overline{\delta\theta_2}) - k_2^{/} * Sin\theta_2]\} \qquad (3)
\end{aligned}$$

Variance Equation:

$$\begin{aligned}
S^2_{G_2} = S^2_{L_{ref\,1,ref\,2}} + (&S^2_{k_0} + S^2_{L_A} + S^2_{R_{A1}} + S^2_{k_1} + S^2_{G_1}) \\
&+ S^2_{G_4} + S^2_{R_{C4}} + S^2_{k_3} + S^2_{L_C} + S^2_{R_{C2}} + S^2_{k_2^{/}})]\} \\
&+ \{[(R_{D6} + \overline{\delta R_{D6}}) * [Cos(\theta_2 + \overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\} \\
&+ \{[(k_5 + \overline{\delta k_5}) * [Cos(\theta_2 + \overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\} \\
&+ \{[(L_D + \overline{\delta L_D}) * [Cos(\theta_2 + \overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\} \\
&+ \{[(R_{D4} + \overline{\delta R_{D4}}) * [Cos(\theta_2 + \overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\} \\
&+ \{[(k_4 + \overline{\delta k_4}) * [Cos(\theta_2 + \overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\} \\
&+ \{[(G_4 + \overline{\delta G_4}) * [Cos(\theta_2 + \overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\}
\end{aligned}$$



SET REFERENCE POINT AT *ref 1*

JOIN CVK SUB-ASSY (107-2) TO KEEL PLATE (107-1)

JOIN FRAME #43-56 (107-3) AND LONG'L GIRDER TO SUB-UNIT (107-1-2)

JOIN SHELL PLATE (107-4) TO SUB-UNIT (107-1-2-3)

LOAD SUB-UNIT (107-1-2-3-4) ONTO PIN JIG

SET REFERENCE POINT AT *ref 2*

LOAD SHELL PLATE (107-5) ONTO PIN JIG AND JOIN ALL TRANSVERSE STIFFENER TO SHELL

JOIN LONG'L GIRDER SUB-ASSY (107-6) TO SUB-UNIT (107-5) ON PIN JIG

JOIN LONG'L GIRDER SUB-ASSY (107-7) TO SUB-UNIT (107-5-6) ON PIN JIG

JOIN SUB-UNIT 1 (107-1-2-3-4) TO SUB-UNIT 2 (107-5-6-7) AT MAIN SUB-UNIT JOINT

Figure 5 Initial Assembly Sequence of Unit 107

1	2	3	4	5	6	7
PRODUCTION STAGE	PROCESS	VARIABLE GROUP	VARIABLE SUBGROUP	VARIABLE - UNIT 107	MEASUREMENT DESCRIPTION	MEASURING TOOL
Parts Fabrication	NC Cutting - 3/4" mild steel	δL	(δL *- 3/4 - ms*)	δL_A	Distance between reference line	Measuring Tape
	NC Cutting - 7/16" mild steel	δL	(δL *- 7/16 - ms*)	δL_B, δL_C, δL_D	Distance between reference line	Measuring Tape
	NC Marking - mild steel	δR	(δR *- ms*)	δR_{A1}, δR_{B1}, δR_{B2}, δR_{C2}, δR_{C4}, δR_{D4}, δR_{D6}.	Distance between plate edge and punch mark reference line	1/32" - Ruler
	NC Marking - X	δR	(δR *- X*)	N/A	Distance between plate edge and punch mark reference line	1/32" - Ruler
	Ink Marking	δR	(δR *- ink*)	N/A	Distance between plate edge and punch mark reference line	1/32" - Ruler
Sub-Unit/Sub-Block Assembly	Fitting - angle joint between 3/4" and 7/16" mild steel plate	δG	(δG *- a - 3/4 & 7/16 - ms*)	δG_1	Distance between reference line on each plate, subtracting distance between plate edge and reference line -Fitting weld gap width	1/32" - Ruler
	Fitting - butt joint between 7/16" and 7/16" mild steel plate	δG	(δG *- b - 7/16 - ms*)	δG_4	Distance between reference line on each plate, subtracting distance between plate edge and reference line -Fitting weld gap width	1/32" - Ruler
	Fitting - other types of joints used in other units	δG	(δG *- x - nnn - X*)	N/A	Distance between reference line on each plate, subtracting distance between plate edge and reference line -Fitting weld gap width	1/32" - Ruler
	Welding - Fillet weld between CVK and keel plate	δk	(δk *- f - CVK & Kplt*)	δk_0	Welding shrinkage - measure difference in distance between reference lines before and after weld	1/32" - Ruler
	Welding - Butt weld between 7/16 " and 7/16" mild steel plate	δk	(δk *- b - 7/16 - ms*)	δk_4	Welding shrinkage - measure difference in distance between reference lines before and after weld	1/32" - Ruler
	Welding - Fillet weld between 7/16 " and 7/16" mild steel plate	δk	(δk *- f - 7/16 - ms*)	δk_3, δk_5	Welding shrinkage - measure difference in distance between reference lines before and after weld	1/32" - Ruler
Unit Assembly	Reference Point Setting	$\delta L_{ref1,ref2}$	-	$\delta L_{ref1,ref2}$	Distance between set reference point for pin jig assembly	Measuring Tape
	Fitting - angle joint between 7/16" and 7/16" mild steel plate (on jig)*	δG	(δG *- a - 7/16 - ms*) - on jig	δG_2	Distance between reference line on each plate, subtracting distance between plate edge and reference line -Fitting weld gap width	1/16" - Ruler
	Pin Jig Angle Setting	$\delta\theta$	-	$\delta\theta_1$, $\delta\theta_2$	Angle setting - measuring height and width of right triangle formed by angle, then calculate angle by trigonometry	Measuring Tape

* indirect measurement is taken.

TABLE 1 Summary of Vital Points and Critical Dimensions

$$+\{[(R_{C4}+\overline{\delta R_{C4}})*[\mathrm{Cos}(\theta_2+\overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\}$$
$$+\{[(k_3+\overline{\delta k_3})*[\mathrm{Cos}(\theta_2+\overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\}$$
$$+\{[(L_C+\overline{\delta L_C})*[\mathrm{Cos}(\theta_2+\overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\}$$
$$+\{[(R_{C2}+\overline{\delta R_{C2}})*[\mathrm{Cos}(\theta_2+\overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\}$$
$$+\{[(k_2^{/}+\overline{\delta k_2^{/}})*[\mathrm{Cos}(\theta_2+\overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\} \quad (4)$$

The geometric equation, equation (2), expresses the variations associated with the components and the variations that are introduced by the joining process at the unit assembly stage. This geometric equation is simply derived from the physical location of points under consideration. Next, the variation equation, equation (3), takes into consideration only the deviation from the nominal dimensions of each variable present in the geometric equation. Lastly, in the variance equation, equation (4), the variance of weld gap G_2 is determined by combining the variances of sub-unit 1, sub-unit 2, and the variances of joining processes.

PRIORITIZING DATA BASE DEVELOPMENT

All variables appearing in equations (2), (3) and (4) must be measured by production. However, by applying the principals of short run SPC, the variables can be classified into groups, which will in turn dictate a measurement plan. The categorization criteria are the similarities of the attributes of the variables and the sources of the variations. The results of the categorization are shown in Table I.

Referring to Table I, the variables are grouped by the measurement method (column 6) and the stage of construction (column 1). As a result, the variable group (column 3) for each stage of construction is determined. Then, within each group, the variables are subdivided into subgroups according to the characteristics of the processes that are the sources of variations (column 2). For example, the variables δL_A, δL_B, δL_C and δL_D belong to δL group, which are the measurement of distances between reference lines at the parts fabrication stage. Then, the δL group is subdivided into subgroups $(\delta L - 3/4 - \mathrm{ms})$ and $(\delta L - 7/16 - \mathrm{ms})$, because differences in plate thickness yield different patterns of variations. In Table I, δL_A falls into the $(\delta L - 3/4 - \mathrm{ms})$ subgroup while δL_B, δL_C and δL_D fall into the $(\delta L - 7/16 - \mathrm{ms})$ subgroup. Using the same idea, the rest of the variables appearing in equations (2), (3), and (4) are classified as shown in Table I.

Based on the vital points and critical dimensions, as summarized in Table I, the data collection and measurement methods must be planned. In the executing stage of the short run SPC system, control charts must be employed in order to achieve an in-control state, so the variation merging equations can be used to perform assembly sequence and mismatch analysis.

VARIATION MERGING EQUATION ANALYSES

After all vital points and critical dimensions are determined and sufficient data is collected, the variation merging equations can be used to calculate the probability of rework. Two types of rework analysis are considered, assembly sequencing analysis and mismatch analysis.

Assembly Sequencing Analysis

Inasmuch as assembly sequence is a major determinant of the merged variation at the weld gap G_2, assembly sequencing analysis is used to determine the best assembly sequence. The best assembly sequence is defined as the assembly sequence that yields the least deviation from the nominal design weld gap, as shown in Figure 6.

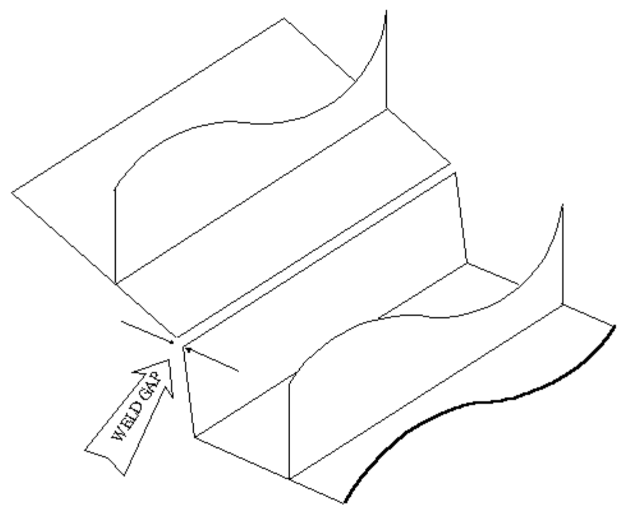


Figure 6 Weld Gap Location For Joining Assemblies

Using the series of variation merging equations developed for the merged variation at weld gap 2, the probability of rework can be predicted. First, with the data collected from production, the mean and the standard deviation (square root of variance) of weld gap variable G_2 can be computed. Then, the distribution of the weld gap G_2 can be generated, as shown in Figure 7. If tolerance limits of the weld gap G_2 are known, the percentage of rework can be computed from the constant *c* in the following equation:

$$\mathrm{Tolerance\_Limit} = (G_2 + \overline{X_{G_2}}) + cS_{G_2} \quad (5)$$

where

$\mathrm{Tolerance\_Limit}$ - known parameter from the standard tolerance; upper tolerance limit and lower tolerance limits,

G_2 - known design (nominal) dimension of weld gap #2,

$\overline{X_{G_2}}$ - known mean deviation of weld gap G_2 (from the database),

S_{G_2} - known standard deviation of weld gap G_2 (from the database), and

c - unknown normalizing constant determining the control limit.

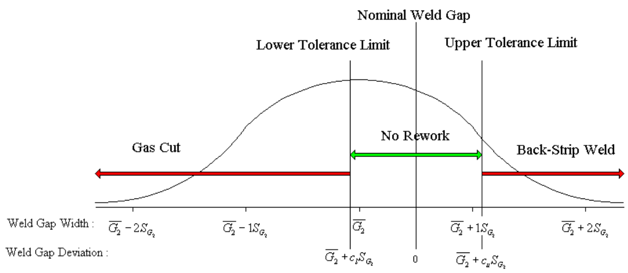


Figure 7 Weld Gap Distribution Showing Rework Regions

In equation (5), the value of variable c can be easily determined. Next, the area under the curve of the distribution of the weld gap G_2 can be determined by using any Gaussian probability distribution (standard normal) table. The percentage of gas cut can be calculated by substituting the lower tolerance limit of the weld gap into equation (5), and the percentage of back-strip welding can be calculated by substituting the upper tolerance limit of the weld gap into equation (5). In other words, if the weld gap is narrower than the smallest permissible gap width, the plate must be trimmed by gas cutting, and if the weld gap is wider than the largest permissible gap width, the back-strip welding process is used. In Figure 7, the shaded-arrow area in the middle section illustrates the no-rework region. Figure 7 is for illustrative purposes only, since the data base needed for this analysis is not yet available. In reality, the proportion of the no-rework region is expected to be much larger. Finally, by examining various assembly sequences, the best assembly sequence can be determined.

In addition to determining the best assembly sequence, the longer term solution can be obtained by linking the result of the analysis with the design. Maximizing the no-rework region can be accomplished by compensating for the variations due to the production process by adjusting dimensions during the design. Also, from the perspective of shipyard management, estimating the amount of rework in advance provides great value to planning and scheduling of production. Finally, from the perspective of process improvement, the results of the analysis can be used as a target for improving process capability.

Mismatch Analysis

Another use of the variation merging equations is to predict the probability that longitudinal bulkheads and girders of consecutive units line up within acceptable tolerances during erection. Figure 8 illustrates the alignment of the longitudinal girders. Mismatch of these longitudinal girders is potentially a major problem due to the structural implications of such a condition. Consequently, a mismatch requires an urgent schedule for rework, or the erection stage could become a bottleneck.

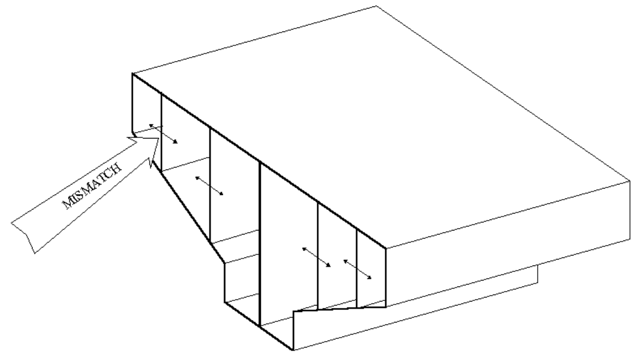


Figure 8 Longitudinal Girder Alignment

Essentially, two approaches can be used to correct this mismatch. If the mismatch is fairly small, the girders can be forced in place by using mechanical methods. However, if the mismatch exceeds the capability of mechanical restraints, the weld seam must be scarfed loose, readjusted, and re-welded.

For unit 107, points 1, 2, 3 and 5 (see Figure 3) are of interest in the mismatch analysis. Therefore, the corresponding variation merging equations are developed to express the pattern of merged variations at each of these points. Unlike the variation merging equations for the assembly sequencing analysis, these equations must take into consideration the variation along both the X-axis and the Y-axis. Otherwise, the form of the equations is identical to those shown previously (equations 2, 3, and 4). To save space, these equations are not presented here, but may be found in [5].

Like the assembly sequencing analysis, the probability of rework is also of interest. However, the mismatch analysis has two sets of tolerance limits, which are called the first- and second-tier tolerance limits (see Figure 9). If the mismatch is within the first-tier tolerance limits, no rework will be done; if the mismatch falls between the first-tier and the second tier tolerance limits (on the same side), mechanical methods need to be applied; if the mismatch falls beyond the second-tier tolerance limits, readjustment of the longitudinal girders is required.

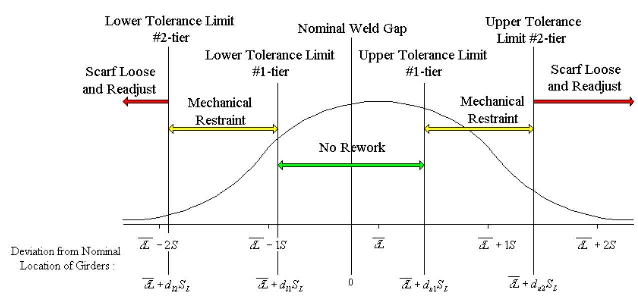


Figure 9 Mismatch Rework Analysis

As explained for the assembly sequencing analysis, the mismatch analysis requires data collected from production as well as the variation merging equations for each point of interest. Then, the distribution of the mismatch can be determined. Finally, the probability of rework can be computed by substituting the design tolerance limits, the merged variation, and the merged variance of each point of interest into the following equation:

$$Tolerance\_Limit = \overline{X_{nn}} + dS_{nn} \quad (6)$$

where

$Tolerance\_Limit$ - known parameter from the standard tolerance; lower tolerance limit and upper tolerance limit,

$\overline{X_{nn}}$ - mean deviation from the nominal of the location *n* reference to *ref n;*

S_{nn} - standard deviation of mismatch location of the location *n* reference to *ref n;* and

d - unknown normalizing constant determining the control limit.

The unknown constant *d* can be determined and the area under the curve in the range of interest can be obtained by consulting the Gaussian (standard normal) probability distribution. As a result, the percentage of each type of rework, at each vital point can be determined (see Figure 9).

Once the percentage of rework is predicted, insight into the process capability will be gained. As a consequence, a shipyard can confidently and effectively make the decision of when to implement corrective action. For example, if the results of the analysis show a the lack of process capability, the short-term solution can be to postpone the final welding until the erection stage, while the long-term solution may be to improve the fabrication process accuracy.

CONCLUSION

In implementing a short run SPC system (accuracy control system), the variation merging equation methodology is employed at two different stages, planning and evaluating. In detail planning, the variation merging equations are used to provide guidance in identifying the vital points and critical dimensions. As a result of the application of the variation merging equations to identify the vital points and critical dimensions, the initial process control effort can concentrate on critical processes that are the sources of variations in critical dimensions. In brief, the purpose of utilizing the variation merging equations at this stage of the system is to maximize the yield of the process control effort.

In the evaluating stage, after the processes are in control and sufficient data is available, the variation merging equations are used to perform assembly sequencing analysis and mismatch analysis. Despite the different purposes, both types of analysis are used to predict the probability of rework. Furthermore, these results can be fed back to the design stage so that the variations are properly accounted for by design dimensions. The final outputs of the analysis activities - including analysis of assembly sequence and analysis of mismatch - can be used to improve the process as well as to improve the design.

Variation merging equations are a powerful tool that can aid accuracy control efforts in a number of ways. This research has verified that the equations can help implement a new system, by prioritizing data base development efforts. They are also very powerful for process analysis and process improvement.

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A Prototype Object-Oriented CAD System For Shipbuilding

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ABSTRACT

This paper reports on the on-going development of an object-oriented CAD system at the Advanced Computer Laboratory for Shipbuilding at the University of New Orleans. It describes a) the reasons for object-oriented (yard-specific) development, b) the computer-aided software development environment, c) the developing class structure of the ship structures design application, and d) the planned developments within the CAD system and integration of packages to support visualization, planning and enterprise management and electronic data interchange.

NOMENCLATURE

AP - Application protocol
CAD - Computer-aided design
CE - Concurrent engineering
EDI - Electronic data interchange
IPPD - Integrated product & process development
ISO - International Standards Organization
NSRP - National Shipbuilding Research Program
ODMG - Object Data Management Group
OLE - Object linking & embedding
OODBM - Object-oriented data base manager
OOP - Object-oriented programming
OOT - Object-oriented technology
PC - Personal computer
SBD - Simulation-based design
STEP - STandard for the Exchange of Product model data
2D - Two-dimensional
3D - Three-dimensional

INTRODUCTION

The work described here is concerned mainly with the use of object technology in software application development. This new technology is changing how computer software is written and maintained. It is changing the paradigms of software development while radically shortening the time scales of that development. The specific project that will be discussed here is that of building a customized computer-aided design system from libraries of geometry, topology, and graphical user interface components. These libraries include entities and algorithms. The goals of this project were to use object technology to create a working prototype of a ship design system, assess its advantages and weaknesses as compared to commercially available systems, and assess the feasibility (or economic justifiability) of in-house development within American shipyards.

The status of this work will be discussed along with sufficient background in object programming and technology, as well as current business trends in information resources, design and manufacturing. There will be some discussion of future efforts in the use of a centralized database of which the product model is an essential element.

BACKGROUND

Generic Computer-Aided Design

The past fifteen years have seen the appearance of computer-aided design (CAD) systems within the design, manufacture, and engineering components of companies worldwide. This has been mostly due to the plummeting price of computing power and the availability of interface-driven operating systems and powerful application packages. The ability to prescribe, describe, and analyze products using computer programs as a primary tool has allowed for a pronounced change in the way that products are conceived.

The question of how to chose a CAD system that will lead to greater success for a company is a difficult one to answer. Cost-benefit analyses are not totally successful in that they do not reflect the culture of a company, and are often based on processes that currently exist and will or should not in the future. These analyses tend to be viewed as pre-arranged - the figures were made to justify the desired outcome. An excellent overview of the difficulty in choosing a CAD system can be found in Marks and Riley (1). This book also offers a superb scheme by which a rational choice could be made.

The phrase "CAD" has taken on numerous meanings due to the vast differences in the scope and power of commercially available packages. CAD can mean as little as creating 2D line drawings (drafting). It can mean as much as creating 3D solid models whether through constructive solid geometry or through 3D boundary representations with topology.

Low end CAD packages are in some ways not very powerful, but still may be viewed as being complex to the uninitiated. They run on personal computers (PC's) running various versions of the Microsoft Windows, Macintosh, or DOS operating systems. Vendors in this area, which are numerous, include AutoDesk, Cadkey, and Ashlar.

These packages also allow for connection to various external software programs that may perform analysis, 3D visualization, or management functions. This connection may be straightforward, accomplished by operating system function, such as MicroSoft Windows Object Linking and Embedding (OLE), or through saved file structure. Often it is the case that the connection is cumbersome, requiring file manipulation that is difficult to automate.

Regardless, these higher level functions are not the key to the succes of these low-end packages. Historically a company's manufacturing processes have been based on 2D line drawings. The

craftsmen that build the product have extensive experience in interpreting this kind of design output. In this sense, 2D line drawings do reflect manufacturing process, they are the seminal element from which manual manufacturing proceeded. It is for this reason alone that low-end CAD packages have been such a success.

High end packages are very powerful and indeed very complex. They run on very high-end PC's or on workstations running some version of the UNIX operating system. They have numerous operations and features in an attempt to surround all possible design algorithms and they include copious optional modules for analysis, manufacturing, and/or management, etc. Vendors in this area include Parametric Technologies, IBM, SDRC, ComputerVision, and Intergraph.

Even though these systems offer enormous power they are not the automatic preference, even for companies that need more than 2D line drawings as design output (for example they may need toolpaths for numerically controlled machines or robots). Some of the problems with these packages are:

- their cost - initial cost, the cost of lost productivity while personnel learn the new system and adapt to it, and the on-going cost of relatively sophisticated systems and computers that require maintenance
- their difficulty to master - their powerful structure leads to complicated interfaces with abundant selections and complex command sequences
- their lack of open communications - even though they have abundant modules for support they don't directly communicate with the company's well honed materials management system
- their overhead of features - they have a large number of options for doing certain tasks, many more than a company will need or use
- their inability to reflect a company's design practices and manufacturing processes.

For these reasons, some businesses have taken off-the-shelf packages and have over time tailored them to the processes and practices of their yard. This is usually a difficult and expensive task but results in a highly effective CAD package. This is essentially how Boeing Aircraft has developed its world renown CAD system. Although it is CATIA, the developers of CATIA, Dassault and IBM, worked extensively with Boeing to provide the functionality that Boeing required (2).

The Information Age. As companies move to cut manufacturing costs through automation and process improvement, it is crucial that information from design be changed to support the new manufacturing methods. To be competitive companies need to be responsive and capitalize on what they do well. The right kind of information at the right place is necessary for optimal operation. Information, in fact, and its management is now the focal point of corporate competitiveness. Creating information and storing it in a central database that is then shared, modified and utilized by all internal units is seen as essential to being competitive.

At the heart of this database is the three dimensional product model (3) which consists of the 3D geometry and topology of the product and its parts, its material properties, its manufacturing processes, its relationships to all other products, maintenance requirements, etc. The database also contains marketing information that may include 3D visualizations, or virtual reality presentations, purchasing information, financial information, etc.

This view of centralized information as the chief company asset is developing in conjunction with the philosophy of integrated product and process development (IPPD) or concurrent engineering (CE). On a philosophical level IPPD is a frontal attack on the design of a product. It is all business units acting simultaneously in combination with the customer to create a design. On a functional level, IPPD cannot succeed as it is intended unless there is high level integration of methodologies and tools, seamless communication between working groups, and a shared database that defines the product. The core of the functionality of IPPD is computers, networks, and information technology. A deficiency in most current CAD systems is that they are very much design and engineering systems. They are not business systems. They are not a ready part of the new IPPD world.

A new facet of IPPD that is currently emerging in manufacturing is simulation based design (SBD). SBD is the practice of using product design knowledge in simulations and visualizations during the design process. As much as possible, the product is "tested" and "reviewed" using software and computers before manufacturing starts. This means physics-based simulation and virtual reality evaluations of the product's structure. SBD requires the geometry of the product as well as knowledge about its physical properties. The 3D product model is needed for this process.

STEP. Another element that is playing a role in the future of CAD is STEP- STandard for the Exchange of Product model data, a standard of ISO (10303). Within STEP are conventions for basic geometry and topology. On these conventions are built higher level entities that are industry specific and these are collected in application protocols (AP). STEP infers a standard format for exchanging CAD data between different software systems. Much of the world is adopting this standard. It will be the neutral format for exchanging data and yet most CAD systems do not have the STEP definitions as part of their basic elements. STEP translators must be created to take a vendor's format (AutoDesk's DXF for instance) and convert it to this neutral format and vice versa. This is not a trivial task. Many CAD systems store geometry and not topology, or their topology is not robust or consistent with STEP. There is currently a funded effort (4) to create prototypes of these translators.

These issues point to the need for a new generation of CAD systems that are part of the whole business process, that are modular, flexible, extendible, and can be tailored to suit a company's strength. These new systems need to provide data that is available to all business units and can be transmitted easily to business partners and customers. Two recent brief articles by Deitz (5,6) review new CAD systems in this light.

Shipbuilding Computer-Aided Design

The level of use of computer aids in American yards (and their impact) has been well documented. Important recent works include NSRP report 0373 (7), and the papers of Storch, Clark, and Lamb (8) and Ross and Garcia (9). A broad overview of computer aids in all aspects of ship manufacture can be found in Latorre and Zeidner (10). A paper by Storch and Chirilo (11) speaks squarely to effectively using CAD for more than basic design function.

Concurrent engineering is being strongly promoted by the branches of the U. S. armed services and is being embraced by several shipyards. It was the topic of three recent NSRP efforts. They are documented in reports 0435 (12), 0436 (13), and 0454 (14).

There are CAD packages that are specifically for shipbuilding. These off-the-shelf products include Autoship from Autoship Systems, FAST SHIP from Proteus, ISDP from Intergraph, FORAN from Senemar, and Tribon from KCS. Both IBM's CATIA and Parametric Technology's Pro/Engineer have recently included ship design packages in their optional modules. These packages like the

generic ones differ greatly in scope and power. Each has strengths and weaknesses. These may not be a perfect fit for any yard but could be profitable solutions in many yards.

The functionality of world-class CAD systems is being reviewed and characterized in an ongoing project funded by the NSRP (15). This project is at a midway point but its interim report supports this idea: world-class does not have to mean cutting-edge technology, but it does mean highly tailored systems that capture and enable what your company does and supports it as much as possible.

As an example that is somewhat different from Boeing's effort with CATIA there is the Danish yard at Odense and the Hitachi Zosen yard in Japan which have developed HICADEC, one of the most successful computer aids in shipbuilding. This development has almost totally been done in-house over many years, but HICADEC has become a powerful tool for these yards which are considered to be among the most competitive and productive in the world.

A significant effort in this area of customization is that of Newport News Shipyards. This shipyard participated in a DARPA funded project for the development of simulation-based design (Lockheed/Martin was the lead contractor). As part of that Newport News has created a smart product modeling system for shipbuilding. This system's architecture is based on several commercial-off-the-shelf products. Entities are created in the 3D CAD environment, placed in a database, and managed by an object-oriented database manager. This allows for those entities (objects) to possess attributes of almost any nature. The information can be queried at any time by the database manager. New information can be attached to an object at any time. Thus, a smart 3D product model exists.

It is the success of these in-house developments that stimulated this research. The lessons that could be drawn were:

- The more a yard could tailor the CAD system to their processes and practices the more valuable it was. For CAD systems to be of the most value they had to be flexible, modular and open.
- The users had to be able to determine their characteristics and functionality. The users had to be able to institute new algorithms that are useful to them alone. They had to be able to remove all functionality that is of no use to them.
- They had to be able to create any standard entity that is necessary for their design or manufacturing, even it is only a standard for them. They had to be able to use terminology that is the practice of their yard.

The success of these in-house developments is so clear one may ask if something similar is the answer for every shipyard. If given the opportunity by software vendors, most yards could eventually tailor commercial products into something extraordinary for their own use. But these developments may take many years, and that is time that American shipyards do not have. They must become competitive on the world market in the immediate future or many will not survive.

One may also ask if something like the Newport News system is the answer. With a product like that one there are dangers in that the future is not totally controlled by the yard:

- The component commercial-off-the-shelf products will evolve and may not remain the component that they need.
- It may not be possible to include newly identified functionality requirements in those core products at a later time.
- It may be that the communication between these products will not always remain clear and seamless.

The questions that motivated this research are: Is it feasible for a yard to build a self-contained state-of-the-art CAD system (a smart 3D product modeling system) - one whose function and input/output can be integrated into all business processes - from scratch? If feasible, what expertise does it require? How many people would it require? What is the time-frame of such a development?

OBJECT-ORIENTED PROGRAMMING LANGUAGES AND PARADIGMS

Object-oriented technology (OOT) is an extension of the paradigms upon which object-oriented programming (OOP) was built. OOP languages are the most current fad in the computer science community. These languages are relatively new (the oldest is about 30 years old) but have really stormed to the front in the world of application development within the last 5 years or so. They are emerging as the unanimous choice for building applications that are centered around the creation, management, and sharing of information.

Computer languages that are most familiar to people like Fortran, C, and Basic are of the oldest type and are called procedural languages. They are used to create procedures for doing calculations or manipulating data, etc. The popular languages just prior to OOP were structured procedural languages. The motivation behind these languages (it was more a style than a new language) was verification of code. Large pieces of code were difficult to verify if the code lacked a formal structure.

OOP languages have very formal structures and that is one of their strengths This structure is based on several definitions and paradigms, some of which will be presented below. OOP languages obviously execute procedures. With OOP, it is how procedures are packaged that is significant.

Detailed information about object-oriented program-ming and technology can be found in numerous books. Among them are those by Meyer (15), Kemper (16) and Burleson (17). A less technical overview can be found in the book by Taylor (18), and a less optimistic view is provided by Webster (19).

OOP Structure

In OOP language programs data and the procedures that operate on that data are packaged together in *objects*, pieces of code that are self-contained in a somewhat similar way that sub-routines in procedural languages are self-contained. Procedures are never written such that they are unattached to data. A *class* is a template for a set of similar objects. A class is a package that contains all of the procedures (called *methods*) and variables for every member of the set. Creating a class avoids needless redundancy of code.

What follows is a short description of four important concepts for object-oriented languages. These four traits embody the power of these languages to improve the structure and design of programs.

Abstraction. The ability to create classes that represent a certain set of data as a new data type is called abstraction. In most procedural languages there are pre-defined data types: real, integer, character, boolean, etc. It is not possible to create a new type of data. In OOP every class can be considered to be an abstract data type. A class represents a whole new data structure that has well defined behaviors and characteristics.

Encapsulation. The feature of packaging together corresponding variables and methods within an object is called encapsulation. It is important because it allows for the details of procedures to be hidden from outside the object. Methods are never passed to objects, only messages. The message asks for some method to execute but the details of the method are not known to the sender of the message. This allows for simple interaction between objects and therefore for easy modification of the methods without

wholesale changes of the code.

Inheritance. The acquisition of methods and variables by a class simply by its position in a hierarchy is called inheritance. All classes are placed in a hierarchy (in some OOP languages multiple hierarchies are allowed). Classes have descendant (or sub) classes that inherit their methods and variables. They have parent (or super) classes from which they inherit. This is a property that eliminates redundancy and encourages consistency.

A program contains classes for closed polygons, quadrilaterals, rectangles, squares, triangles, and isosceles triangles. In the hierarchy, quadrilaterals and triangles inherit from closed polygons. Rectangles inherit from quadrilaterals and squares inherit from rectangles. Isosceles triangles inherit from triangles. When the message is sent to any member of the class square to provide its area, an appropriate method executes. A "compute area" method could exist in the class square, but one also exists in the class rectangle. The class square could inherit the method of computing area from the class rectangle, which may or may not inherit the method from the class quadrilateral. The same scenario exists for the triangle branch of the hierarchy.

Polymorphism. The ability to hide different responses to a single message behind an object's interface is referred to as polymorphism. In the hierarchy above, if the message of "provide area" is sent to a member of the class square or triangle, they both respond with their areas even though the method used to compute the areas is different. The message sent is simple - "provide area." The response it elicits is the same as seen from outside the object. This feature of OOP allows for simple and consistent interaction between objects.

OOP Languages and Database Managers

There are pure OOP languages and there are hybrid ones. The most important of these would include Simula (the original), SmallTalk, and now Java, which are pure OOP languages. Objective-C and C++ are hybrid OOP languages, both being OOP extensions of the language C. Both of these languages allow for procedural code to exist along with object-oriented code. They were created to take advantage of the power of C at doing some procedural tasks.

The language chosen for this development is C++. C++ can be said to be arcane and has some very challenging features that are not good for beginning programmers, but at this time it is the most commonly employed OOP language. There is no ANSI (or other) standard for C++ at this time, which means that every vendor's C++ compiler has different capabilities.

Object-oriented database managers (OODBM) use the paradigms set forth above. Because they do they offer a powerful way to store complex data structures. Relational databases were designed to store conventional data types: real numbers, character strings, boolean values, etc. When you have created a hierarchy of objects, each of which can be considered to be an abstract data type, relational databases cannot directly store that information. The OODBM can store that information just as it is and can then query it. It does so by storing references between a class and its instances, between objects and other objects. So a composite piece has references to all of its components - all of the variables that are related to it. They could be character strings, real numbers, topological characteristics, geometry, a rasterized drawing, a bill of materials, etc.

The manipulation and communication of objects as described above is standardized by a working group called the Object Data Management Group. Their standard ODMG-93 is generally accepted in this area.

OOT Conclusion

It is because of these traits of object-oriented technology that it is currently the choice for development of complicated software applications. It offers the ability to build applications in a highly modular way with abstract data types of any nature. Data and procedures are always associated with their pertinent objects. This leads to code structure that can be more easily verified to work. Changing code to include new features or to modify existing ones can be done with limited re-writing of existing code. OOT leads to data structures that can be highly heterogeneous and yet very usable.

In closing, the reader is reminded that the word "object" is used in a lot of different contexts concerning computers. One of the most frequent uses is in conjunction with MicroSoft's Object Linking and Embedding (OLE). This technology is very different from what is described here. Not all of the paradigms listed above actually pertain to OLE. OLE is a very rigorous and useful standard but one that only exists in MircoSoft's Windows operating systems.

DEVELOPMENT ENVIRONMENTS

One option for development would be to buy a C++ compiler and start from scratch. That clearly carries a lot of risk. If that were the only option then developing an in-house CAD system would not be justifiable. Fortunately there are toolkits that are available that makes this process possible and warranted. These toolkits include those from ComputerVision Corp. (Pelorus) and Matra Datavision (CAS.CADE - computer-aided software for computer-aided design engineering). The details of these toolkits differ considerably but they have both have the elements needed to create OOP CAD applications. The toolkit or development environment used here is CAS.CADE.

The environment consists of a methodology for creating applications supported by appropriate tools and a set of expandable C++ class libraries. These libraries include classes for modeling, analysis, graphical presentation, graphical user interface implementation using Motif constructs, and data management. There are extensive libraries for creation of geometry and topology, in both 2D and 3D. These two libraries are STEP compliant. The basic entities were created using STEP Part 42 definitions. These libraries support non-manifold topology.

For both of the environments mentioned above finished applications can be deployed on machines running versions of the MicroSoft Windows operating system. They also required a language compiler, either MicroSoft Visual Basic for Pelorus or Visual C++ for CAS.CADE.

The brief description below is meant to impart a notion of possible elements in a robust environment for the development of CAD. The various types of software components (development units) are given these names (see Figure 1.):

- a set of related classes is called a *package*
- a set of data types known to an application database is called a *schema*
- a set of related packages can be formally grouped together into a *toolkit*
- a set of packages, classes, and methods whose services are exported to the front end is called an *interface.*
- a set of interfaces is called an *engine*
- a set of chosen engines make up an *application*

This categorization reflects the modular nature of development.

Pieces are constructed from smaller pieces, and so forth.

In example, an application would include a dialogue engine which implements the ergonomics of the user-interface. It handles all of the user-initiated screen events (whether graphical, button, menu selection, or text) and passes them to the front-end. The front-end is basically the software driver of the engines - it calls scripts that cause messages to be sent to appropriate objects and thus actions are taken. The application engine (there could be more than one) would provide all of the functionality that the user expects in terms of object creation, algorithmic behavior, and data storage.

Referring to Figure 2., the development concepts can be seen. The development is structurally formalized by the use of a definition language. Using this concise language new classes are defined. The definitions are then compiled and the results stored in the data dictionary. At this point the compiler creates an appropriate C++ template and header for all of the methods for all of the defined classes. The user takes these templates and completes them thereby creating his/her desired procedures.

Figure 1.

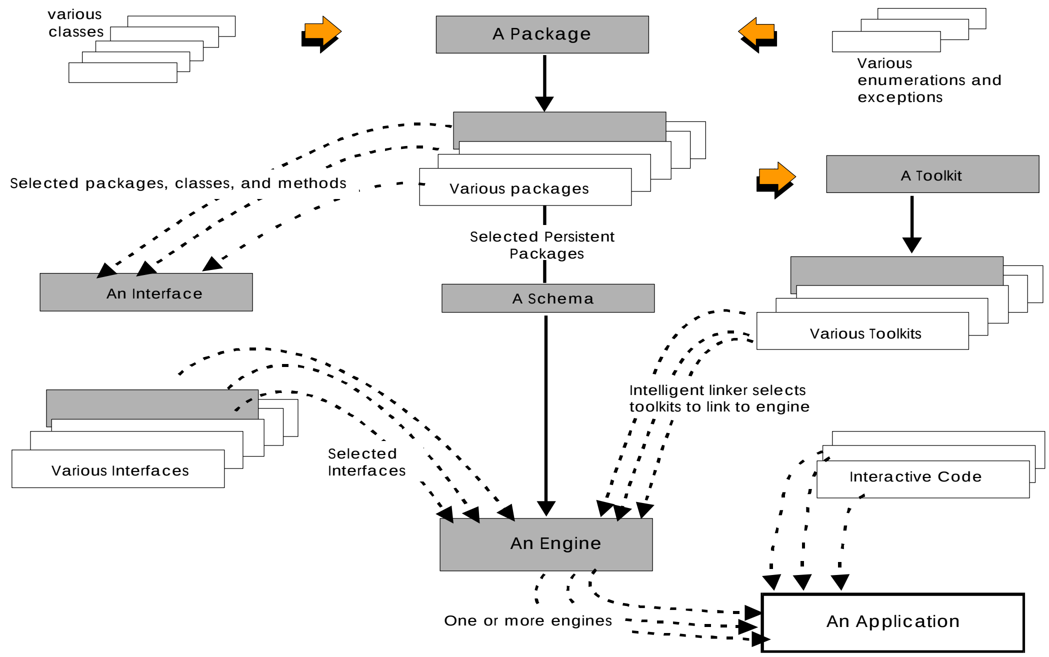

Figure 1. Development environment units and their roles.

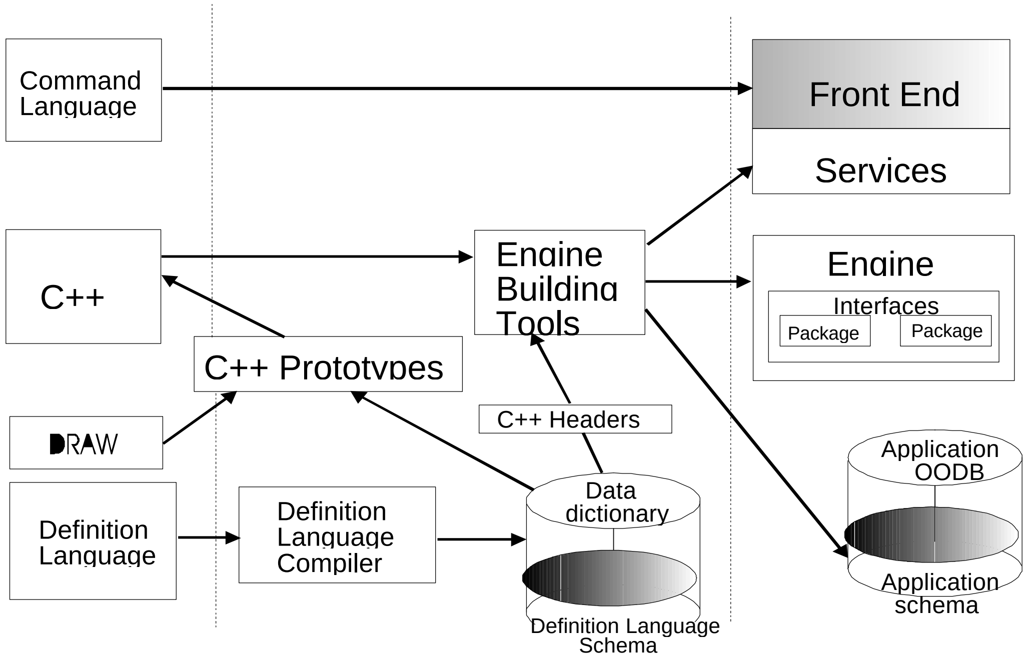

Figure 2. Development schematic

The data dictionary is central to the workings of the environment. By its presence in the dictionary, a class is available for instantiation - objects of that class can exist (C++ headers are then available). Its place in the hierarchy of classes is known, both in the software and in the database. Therefore the database structure is being built as the application is being developed.

The environment also includes a command language which is an interpretive scripting language. It is available for writing front-end scripts and for interacting directly with an application engine. It is especially useful in building the graphical user interface and graphical applications. It allows for debugging semantics and syntax without constantly re-compiling the C++ code.

One other important piece of the development toolkit is the draw environment. Draw is a wire-frame presentation environment where one can create and present objects without having the whole graphical use interface running. This allows the user to write, visualize, and debug the C++ code that executes procedures in a rapid fashion.

This toolkit provides all of the functionality required to create a stable customized CAD system with a self-consistent object-oriented data structure. Although the detailed workings of Pelorus are quite different, it too offers the same results. Fairly powerful workstations are required for these environments. For this work, the toolkit is running on a DEC AlphaStation 250 running Digital UNIX. The workstation has 2 GB of hard disk storage and 128 MB of memory.

A PROTOTYPE CAD SYSTEM FOR SHIP STRUCTURE

One of the prototypes in development is that of a preliminary design system for containerships and it is within the scope of this prototype that this discussion will proceed.

Application Specifications-

The first step in the development of a prototype is to list its specifications. These are the sequences of tasks that are used to design a piece of the product, for instance, the parallel midbody. This enumeration should be done by the current designers themselves with some input from manufacturing. This input is needed to make sure that current or proposed fabrication practices are being reflected in the design sequences and tasks. This should be done with the attitude that process improvement should always be a primary goal.

These detailed specifications should be of the intent of a task and not of the actions taken to accomplish the task. To clarify the difference, the intent of the task of creating the hullform in the parallel mid-body section of a ship could be stated as, “The hullform should have a flat portion on the bottom and a flat portion on the vertical. In between, it should have a curvature of constant sign and the whole surface should be continuous and have two continuous derivatives”. That is the detail of the task. It is the “what to do.” In contrast, a specification of action would prescribe a way of creating that surface. It could be stated by, "Create the hullform by creating a piecewise continuous polynomial surface that passes through a set of prescribed points". This is the “how to do it” and that should not be done at this initial step.

Class Hierarchies

The next step is to create the class hierarchies and appropriately assign the procedures as methods to them. Some classes are obvious while others are not and a developer needs to use the product as a guide in creating these classes.

One of the benefits of using OOP to do this development is that the standards that are in place or are developing for the exchange of ship related CAD data are very much class hierarchies. The two important ones are the application protocols for STEP and NSRP (20). The STEP AP for ship structures has not yet been adopted and it is not likely to be adopted in the near future. The NSRP standards exist and are apparently fixed. Although the basic geometric and topological entities of the development environment are based on STEP definitions, this does not include high level entities such a stiffeners, decks, bulkheads, etc. Since the STEP ship structures AP is not yet finished, the NSRP standards have been used for guidance in developing the structure class hierarchy.

As an example of the guidance found in the NSRP standard, the application object ship_edge described in section 4.2.536 is

envisioned to be a subtype of the ISO 10303 Part 42 entity. Section 4.2.566 describes a ship_seam. This is not a subtype of Part 42 but it is according to NSRP a type of ship_edge. It is clear, ship_seam is a class that inherits from the class ship_edge.

Stiffeners can be created using a profile and sweeping it along some curve to create a solid. In terms of geometry the profile is a set of curves or line segments that form a closed loop. In terms of topology these curves constitute an *edge* which bounds a *face*. The topological *face* is used to create a *solid* by sweeping or piping. This action creates new *edges* and *faces* - the defining boundary topology of a solid.

Defining a class for stiffeners allows all manifestations of stiffener to inherit the methods that can be used on this geometry and its associated topology. Classes for prismatic and curved stiffeners can be created and they will inherit from this class. In the NSRP standard, there is an application object called structural_part (4.2.691). It is the highest level object in the hierarchy of parts used to build a structure. One of the types of structural_parts is strucutral_shape_part (4.2.756). One of the types of strucutral_shape_part is structural_stiffener (4.2.785). This clearly suggests an appropriate class hierarchy.

Using NSRP application objects in this way, a nearly complete ship structures class hierarchy can be created. There need not be strict adherence but for the near future there is certainly a strong impetus to follow the NSRP standard. Even if the NSRP names are not used explicitly as class names they can be included in the class definitions as variables or attributes.

An example of one facet where adherence may not make sense is in the definitions of certain surfaces. The NSRP application objects that are used by the unit of functionality molded hullform includes hull_offset_definition, hull_surface_definition, and hull_wireframe_definition. In terms of STEP Part 42, a molded hullform is a surface which can be defined as a Bezier surface or a NURBS surface (there are other choices), but a surface cannot be defined by a set of points or by a wireframe. A set of points, a polygonal faceted surface, or a wireframe may be used to represent the hullform on a computer screen, but these are presentation methods and do not constitute a definition of a surface.

Prototype Completion

Once the hierarchy is established then the methods can be allocated to their proper places. The procedures for the tasks are now chosen and the appropriate C++ code is written. There are usually numerous ways to accomplish a task and choices need to be made with caution. The robust and efficient nature of the resultant CAD system is affected greatly by these choices. The assignment of methods demands care because of the property of inheritance. A properly placed method can help minimize the amount of code needed. As with the example regarding polygons the method for calculating and providing area could be in the class quadrilateral and the class rectangle simply inherits it and then square inherits it. The general method should be at its highest possible level in the hierarchy where as many classes as possible can inherit it. If a more specific method is desired for a subclass then it can the defined in that class.

It is at this point that the development environment is used to create the application engine in the manner described above.

A somewhat similar process is followed for the development of the hierarchy of the graphical user interface. There is much less guidance available here and the satisfaction gained from the look, feel, and functionality of an interface is very much decided by taste. The creation of user the interface is something that requires serious thought. A developer can easily create an interface that offers too many options and features and is therefore overwhelming or confusing for the user. A key philosophy in this area is "keep it simple," - only the functionality that is truly needed should be added to the interface. "Lean and mean" interfaces are more computationally efficient and lead to more efficient use.

CONCLUSION

An enterprise-wide, rich database, of which CAD data is only a part, is the foundation of modern manufacturing methods. Information is a company's key asset and computer-aided design systems are in the broad sense business systems which create information. They are not isolated engineering tools. To maximize company performance CAD systems need to be tailored to a company's design, manufacturing, and business practices. CAD systems need to capitalize on a company's strengths, help streamline and improve the design process, and shorten design cycle times. A purely customized CAD system would be best if it is possible and economically feasible.

The current choice for developing information-based applications is object-oriented technology. The power of this emerging technology lies in its features that are extremely well suited for large applications with heterogeneous data types. It is feasible for a company to develop a totally customized CAD system using commercially available object-oriented programming toolkits. These toolkits contain the needed features and tools to develop a CAD system, and without these such development would not be economically justifiable.

A shipyard can build a self-contained state-of-the-art CAD system (a smart 3D product modeling system) customized to shipbuilding and to the yard itself. There exists significant guidance on how to build the structure of such a CAD system in the standards of the NSRP and STEP.

It is feasible to do so but it is not a trivial task, even with the development environments available. It requires a clear understanding of the existing or proposed processes in the yard. It requires expertise in object-oriented programming languages and technology. Obviously having people on board who already are proficient in object-oriented programming would help a great deal, but today those people are in great demand and not easily hired or retained. It is easier for a yard's employees to learn to program than for a yard to hire experienced programmers. Engineers and designers that can somewhat program are preferable to programmers who can somewhat engineer or design. It does not require people with 10 years of programming experience or masters degrees in computer science, but it does require training.

It very difficult to judge the time-frame of such a development or how many people it would take to build an in-house CAD system. A best guess is that 6 to 10 productive people who have been adequately trained in object-oriented programming could get a fairly sophisticated system running in 6 months.

It is not the long term goal of this research to produce a complete CAD system. Work will continue on components to clarify the feasibility of in-house development and to prove the value of object-oriented technology in design and manufacturing applications. Future efforts are planned to use the CAD database in a planning and enterprise management system, in a virtual reality environment that supports simulation based design, and in an Internet-based information interchange application. In each of these areas, object-oriented toolkits exist and each should be able to use one common database.

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